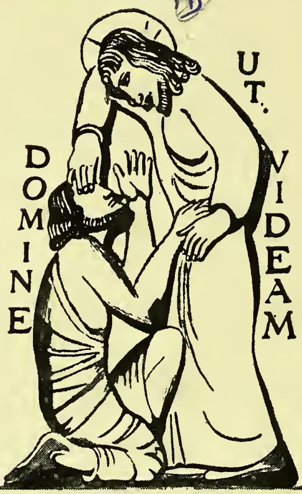
RESEARCHES IN COLOUR VISION

AND THE TRICHROMATIC THEORY

SIR WILLIAM ABNEY



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RESEARCHES IN COLOUR VISION AND THE TRICHROMATIC THEORY

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AND THE TRICHROMATIC THEORY

BY

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WITH 4 COLOURED PLATES AND OTHER ILLUSTRATIONS

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PREFACE

The author has brought together in book form the substance of a somewhat large number of communications which during the last twenty-five years he has made to the Royal Society, on the subjects of Colour Photometry and Colour Vision.

The publications of the Society are not always accessible to general readers, more especially to foreigners, and perhaps as a consequence the author has frequent requests for copies of his collection of papers. These requests are one reason for issuing this work; but another one, more cogent, was his wish to show that the Trichromatic Theory of Colour Vision does not yet require a funeral oration over its remains. It is not by any means as moribund as some seem anxious it should be considered, but is, in fact, very much alive. Other theories of Colour Vision, physiological and psychological, have been offered in the press, in magazines, or in books; but the one theory which alone takes cognisance of the physical aspects of the subject has had no such aid to publicity in recent years. In 1891 the author published a small elementary work on the modes of measuring colour, and later, in 1895, a reprint of his Tyndal lectures, delivered at

the Royal Institution, which gave the then state of the Trichromatic Theory, was also published. To make further advances, accurate measures of the three sensations existing in the spectrum colours were necessary. These measures having been made, a new base was established from which an attack on various problems that had been left indeterminate could be delivered. This present publication gives solutions of at least some of these problems. The author has not criticised in it any rival theory, but has confined himself to giving an account of his own researches in regard to the colour sensations, colour blindness, retinal fatigue, and the like. He trusts he has shown that all the phenomena he has studied, and to which quantitative measurement can be applied, are explained by this Physical Theory. There are some after-effects of light on the retina which, so far, do not lend themselves to exact measurement by physical means. These have not been discussed.

A theory, to be one of perfection, must offer the truth, the whole truth, and nothing but the truth. The Trichromatic Theory offers the truth: but the physiologists must add their quota to it to make it the whole truth. There may be difficulties in welding together the physical and physiological aspects of Colour Vision to make a perfect theory, but it will be effected.

There is such a striking likeness in the behaviour of the photographic plate with that of the retina when subjected to the action of light, that it is hard

to believe that the chemical decomposition of sensitive matter (which is admittedly the result on the former) is not the result on the latter. Until the seat of visual sensation is definitely located, no conclusion as to the similarity of result can be arrived at.

This work is divided into Part I. and Part II. Part I. is elementary to some extent, and has been the subject of lectures to students. This part need not, of course, be studied by advanced workers, except so far as is necessary by the references made to it in Part II., where Colour Vision is the main subject. Paragraphs in square brackets may be omitted in reading.

The author has to thank Dr. W. Watson, F.R.S., for advice and criticism in some of his later work. He wishes also to acknowledge the devotion which his assistant, Mr. W. Bradfield, has shown in forwarding his experimental work from its commencement.

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PART I

RESEARCHES IN COLOUR VISION

CHAPTER I

INTRODUCTORY

In writing on the subject of colour, it is not intended to enter into its very elementary aspect. It is taken for granted that the reader is acquainted with it. It is only proposed to give a brief recapitulation of the main facts as generally known regarding colour, and to make these the foundation of subsequent remarks.

Colours have no objective existence; they are simply sensations excited by light as a rule; though an electric current, or mechanical pressure of the closed eyes, may also be able to give similar sensations. With these two last we have nothing to do, and it may be assumed that we are dealing with the sensations that light alone excites on the retina.

It has to be remembered that all bodies can only be recognised by the eye when they are either self-luminous or illuminated. Self-luminous bodies are such as the sun, the arc light, the oxyhydrogen light, candle flames, and gas flames. There are other bodies which are made self-luminous by phosphorescence and by electric action, but these latter we may dismiss for our purpose.

Pure Colours.

Pure colours are produced by definite vibrations of the surrounding ether. For instance, the pure colours

of the bright lines in the spectrum of metallic vapours are each produced by the stimulation of the retina by vibrations of ether waves of different lengths. Impure colours are produced by the stimulation of the retina by more than one set of vibrations, but it is quite possible for an impure colour to match a pure colour. Thus the mixture of the colours about the D (sodium) line in the spectrum will be indistinguishable from the D light itself. The retina does not analyse the mixed colour, but only recognises when the two are similar. We shall see hereafter that even with one set of vibrations the colour recognised by the eye is not always the same, the colour being dependent on the intensity of the vibration, which is equivalent to saying, on the amplitude of the wave.

The pure colours are produced by sending a beam of white light (such as that of the sun or of the electric light) through a prism, which sorts out, as it were, the different wave-lengths. The colours become visible when they fall on a white screen (*i.e.* which reflects white light unaltered). If the beam of white light be sent through a narrow slit before falling on a prism (the slit being parallel to the edge of the prism), and is received on a lens, there will be a band of colours, each colour being an image of the slit when received on a screen (or viewed through an eye-piece) placed at the focus of the lens.

(We have mentioned white light, and it may be advisable to say at once that there is no fixed standard of white light at present. In Chapter V. we shall see what light is most convenient to use for experimental purposes.)

The colours seen on the screen will be red, orange, yellow, green, green-blue, blue, and violet, blending into

one another; and if sunlight be used for the white light, dark lines, some more marked than others, will make their appearance, three of these latter, known as A, B, and C, being in the red, D in the yellow, E and *b* in the green, F in the green-blue, and G and H at the two ends of the violet. These lines are always in the same positions in the solar spectrum, and may be looked on as milestones from which measures of the wave-lengths of intermediate colours can be determined.

Another method of producing pure colours is by means of the diffraction grating, which is made by ruling fine, equally-spaced, parallel lines (as many as 150,000 to the inch and even more) on glass or metal on which white light coming through a distant slit parallel to the ruling is caused to fall. Using a lens to collect the rays, and receiving the focused image of the slit on a white screen, it will be seen that, as well as a colourless image of the slit in the axis of the lens, there are several pairs of spectra on each side of it, the pair nearest it being shortest and brightest; the other pairs being fainter and longer. The number of pairs is theoretically infinite; but practically the first three pairs are well visible on the screen. The central image is formed by half the white light, and the first pair of images take about a quarter for their formation, so that practically the brightest image is, roughly, only an eighth as bright as a prismatic spectrum of equal length with the same amount of light passing through a slit of equal width. Hence for a bright spectrum it is advantageous to use the prismatic rather than the grating spectrum. What is said here is an approximate statement, much of the brightness of the spectra depending on the ratio of the width of the lines to that of the space between them.

No pigments can accurately represent spectrum colours, but we give the nearest approach to them that we know. For the red, the nearest approach is ordinary vermilion (not scarlet vermilion), with which is mixed a small quantity of permanent violet; for the orange, orange cadmium; for the yellow, chrome yellow; for the green, a mixture of prussian blue and aurelin; for the blue-green, viridian, with a small amount of cobalt blue; for the blue, ultramarine; for the violet, permanent violet, to which a little blue is added. With these colours a fair representation of the spectrum may be painted, but it will lack purity and luminosity. These last essentials bring us to state the constants of colours. Besides purity and luminosity, there is hue. When these three are known, the colour is defined.

Colour Constants.

The hue of a colour is recognised regardless of its purity and luminosity. In Chapter XVII. we shall find that the hue of a spectrum colour varies with the amount of white which it contains, the addition of white in some cases giving a hue which is yellower than when it is absent. The purity of the colour is dependent on the amount of white mixed with it. In Chapter X. we find that most colours of nature and of pigments can be matched with one spectrum colour, if mixed with white in varying proportions. It follows, then, that nearly every colour except a spectrum colour is an impure colour. The third colour constant is the luminosity of the colour. In Chapter VIII. we shall find that the luminosity of the spectrum has a decided influence on the hue of a colour, and not only of the hue, but of its apparent purity; for there is a certain

reduction at which the colour (and even the light itself) disappears. From this consideration of the constants of colour, it shows how careful an experimenter must be in drawing conclusions from the results of observations he may have made.

Absorption and Obstruction.

We shall notice in succeeding chapters that we send light through different media ; if the light passes through readily, we call them transparent media. If the light is scattered internally, in its passage through it, they are translucent media. In some cases the medium may be transparent to long wave-lengths and translucent to the shorter wave-lengths, as when light passes through a turbid medium such as water charged with very fine particles. We have in this last case to differentiate between what is true absorption and simply obstruction. We shall find that the coefficients of absorption and obstruction may take the same form mathematically, but not always so. As an example of absorption we may take black glass, and of obstruction the silver deposit of a photographic negative. In the one case certain of the rays of white light are blotted out and perform work in the interior of the glass. In the other the white light itself is more or less arrested according to the number of silver particles it encounters, and the part that is prevented passing through may be partially absorbed by the silver particles and the remainder scattered throughout the glass.

It may be useful to point out what absorption of light entails. Suppose we examine a spectrum through an orange glass, we at once see that a very little red and orange and yellow are absorbed, but that in the

green the absorption is much stronger, and that the blue is totally absorbed. Evidently the coefficient of absorption increases as the blue is approached. If the amount of light cut off by one glass from the different spectrum colours is measured, the coefficient of absorption can be found for each colour. If another orange glass be placed in contact with the first, the amount of absorption of the different colours can be calculated by using the coefficients. The addition of other orange glasses to the first one will reduce the blue-green, green, and yellow-green light passing through them much more than the red, orange, and yellow, and the result will be that naked white light, viewed through these superimposed glasses, will appear reddish orange. This indicates that the colours of different transparent media alter in proportion to the colouring matter present. In some cases, such as, with a solution of methyl violet, where the green is cut out of the spectrum, the coefficients of absorption for the blue are greater than for the red. By increasing the thickness of fluid through which the spectrum passes to the eye, the blue will disappear when the red is still bright. Examining white light through the thicker solution, it will appear ruddy instead of violet. This phenomenon is sometimes called dichroism.

Colours of Pigments.

The colour of pigments is due to absorption. When a pigment is painted over a white ground, part of the light which strikes the fine particles composing it passes through them, falls on the white surface and again strikes the particles, and is received by the eye of the observer. There is part of the light, however, which is reflected from the sides of the particles and does not

traverse them, and also comes back to the eye. The mixture of the coloured light and the white gives the sensation of paleness to the colour. When the pigment is put on so thickly that the white ground is completely covered, the true colour of the pigment mixed with a small surface reflection of white light is seen by the eye. In using colour discs (see Chapter XI.), it is generally desirable that the white card should be entirely and thickly covered. It should be noted that, so far as the colour itself is concerned, the light has to pass through the pigment layer twice. If the pigment be spread upon glass and the eye receives the transmitted colour, the saturation will be much less, though the colour will be the same as that seen by reflected light.

CHAPTER II

THE EYE

Before proceeding further, something must be said regarding the apparatus with which we can perceive colour and light. We join light with colour, as we shall see later on. It is necessary to do so.

Structure of the Eye.

The structure of the eye may be roughly divided into two parts; somewhat in the same way we can divide a camera into two parts—(1) the optical part, and (2) the impression-receiving part. In the camera the first is the lens and the second the plate. In the eye the first is the optical mechanism and the second the retina. The following figure[1] gives a section of the eye, in which the several parts are more or less distorted as to relative sizes.

S*cl* is the sclerotic coat shaded longitudinally, which is continuous with *e c*, the transparent cornea (unshaded). C*h* is the choroid coat, with (C P) ciliary process and (I) the body of the iris, all shaded to show they are parts of the same vascular movement. R is the retina or inner wall, and P E pigment epithelium or outer wall of the retinal cup. In front of the wavy line *o s* (ora

[1] The general description of the anatomy of the eye is taken from Foster's *Text Book of Physiology*, and the author is indebted to its publishers (Messrs. Macmillan) for permission to do so, and also for the loan of Fig. 1 and Fig. 2.

serrata), the retina proper changes into the pars ciliaris retinæ, *p c* R. Both the pigment epithelium and the *p c* R are shown as continued over the back of the iris, as well as over the ciliary process, C P. L is the lens and *s p* the suspensory ligament. V H is the vitreous humour, and the dotted line round one side of the lens and through V H represents a membrane which indicates an embryonic continuation of the central artery of the retina passing through O N, the optic nerve connected with the brain. O X is the optic axis of the lens.

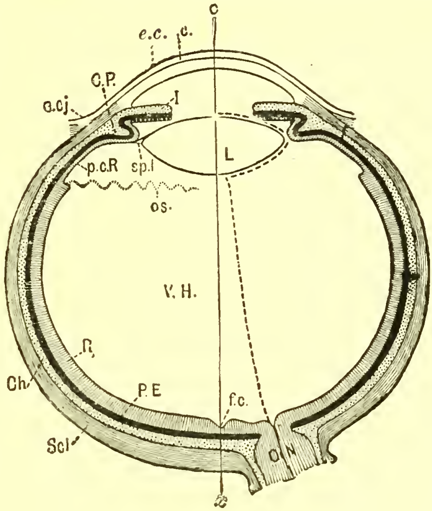


Fig. 1.

Diagrammatic Eye.

It will be seen that the retina is really an outcrop of the brain. The optical apparatus is complicated by the fact that the various refractive indices of each part of it vary. The following table shows the variations :—

Refractive index of the vitreous humour . .	1·3365
Refractive index of lens	1·4371
Radius of curvature of cornea	7·829 mm.
Radius of curvature of anterior surface of lens .	10
Radius of curvature of posterior surface . .	6
Distance from anterior surface of cornea and anterior surface of lens	3·6
Thickness of lens	3·6

These measures allow a reduced or diagrammatic

eye to be calculated, and the rays of light which are brought to a focus on the retina can be traced readily.

Fig. 2 shows the path of the rays on to the retina, and through the lens as calculated coming from the

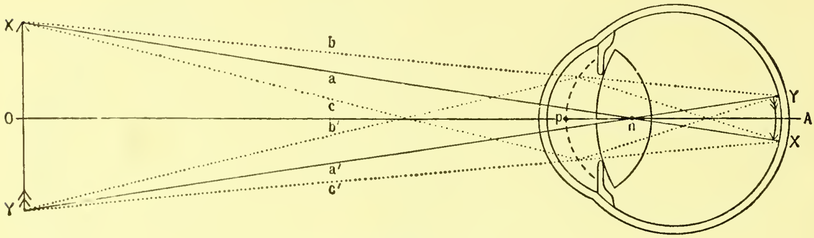


FIG. 2.

arrow X Y and forming the image Y X on the retina. It will be seen that the image is inverted.

In Fig. 1 we have alluded to the *sclerotic coat.* It consists principally of bundles of white fibrillated connective tissue. Part lie longitudinally and part horizontally, and present an interlaced appearance, thin but tough. It is scantily supplied with blood-vessels.

The *choroid coat* consists principally of blood-vessels and muscular and nervous elements embedded in connective tissue. It nourishes the retina, and serves as a muscular mechanism as well. The choroid coat is an elastic coat, which the sclerotic coat is not.

The *ciliary process* (C P in the figure) is a continuation of the choroid coat, but of different structure. Cells which are embedded in it bear pigment, especially in dark eyes.

The *pigment epithelium* (P E in the figure) is composed of plain cubical cells which are loaded with pigment except in albinos.

The *iris* (I in Fig. 1) is a continuation of the choroid coat, which has distinctive features of its own,

and ends abruptly at the pupil. It has round the margin of the pupil muscular fibres gathered together in the form of a ring (the *sphincter iridis*).

The *cornea* consists of connective tissue, which is arranged in concentric layers of bundles, all placed evenly in the same direction. These bundles and the substance cementing them together are all transparent. The front surface of the cornea is covered with an epithelium, also transparent.

The *ciliary muscles* are between the sclerotic and choroid coats, with roots near the iris.

The *lens* L is a transparent body of a certain refractive power, and possesses considerable elasticity; its shape may be altered by pressure, but it resumes its original shape when the pressure is removed. The liquid in the lens is of a globulin nature, approaching to vitellin found in the yolk of eggs, but albumen is absent.

The *vitreous humour* (V H in Fig. 1) consists of a jelly-like material containing principally water. It may here be mentioned that the media of the eye are fluorescent; a condition which is said to be conducive to seeing the ultra violet rays, though, for our own part, this appears very doubtful, being more likely to give a green or violet veil covering the retinal images.

The Retina.

We next have to consider the retina, and this we can only do in a very general way, since it is very complicated in structure. The optic nerve, as has already been stated, is an outcrop of the brain. A vertical section of the retina, which has an average thickness of ·15 mm., shows that it is made up of layers superimposed the one on the other, and these layers are

very much the same throughout the retina, except at one part, the macula lutea (or yellow spot, as it is called), which contains a depression called the fovea centralis.

The layer next the vitreous humour is what is called the layer of optic fibres. The next is a layer of large branched nerve cells. This is succeeded by a peculiar layer, which has a close resemblance to the matter of a part of the cerebellum. Next are two layers of what are called closely packed nuclei. Outside of these comes the remarkable layer of rods and cones, which is probably the seat of visual impression, and which is seemingly in actual connection with the optic nerve, and this in its turn is succeeded by the layers of pigmented epithelium, to which we have already alluded. Each rod consists of two distinct parts of a wholly different nature, called the outer and lower limb. The outer limb is a cylinder about $\frac{3}{100}$ mm. in length and $\frac{2}{1000}$ mm. in diameter. It is transparent and doubly refractive, and is probably made up of a very large number of discs, of about $\frac{6}{10000}$ mm. in thickness cemented together. The cylinder is sensitive to light, swelling up under its action, and shrinking again when the light is removed. It is coloured with a pink matter, which is called visual purple, and which bleaches under prolonged exposure to light. The inner limb is truncated, and tapers to a delicate thread, which eventually connects with the optic nerve.

The cone, like the rod, consists of an inner and outer limb. The outer limb is conical and not cylindrical in form, and is about $\frac{1}{100}$ mm. in length. The inner limb is very like the inner limb of the rod. Excluding the macula lutea, the rods are much more numerous than the cones, though towards the periphery of the retina

the cones become more numerous. The total number of cones has been calculated as being more than three millions.

The macula lutea, or yellow spot, is oval, subtending an angle of about 6° in its longest axis, and 4° in the shortest. As its more common name indicates, it is distinguished from the rest of the retina by its yellowish brown colour. At its edges, the oval is slightly thickened, but in the centre it becomes very thin, and is there termed the fovea centralis, and is about ·3 mm. in diameter. The general character of the layers in the macula are pretty much the same as in the rest of the retina, except that the cones are more numerous than outside. The rods diminish in number as they approach the fovea centralis, where they are altogether absent. The colour is due to a pigment staining one or more of the layers, but is said to be absent at the fovea. The yellow spot we shall have to take into account in our experiments. It is a continual source of difficulty in making measures, more particularly as the amount of colouring matter often varies in different observers.

Zone of Distinct Vision.

Another feature of the optical arrangements and the retina is that there is a zone of distinct vision near and around the axis of the eye. When we look at a small point of light, such as a star, the image falls on the fovea centralis. When two points of light subtend an angle less than about one minute of arc, the two images are blended one into the other, and the separation is not noticed. Calculating the distance apart on the retina on which the two images fall, it is found that they are about $\frac{4}{1000}$ of a millimetre apart. In the human eye the

distance apart of the cones are about $\frac{4}{1000}$ of a millimetre from centre to centre, and the diameter of a cone is somewhere about $\frac{3}{1000}$ of a millimetre. Hence if the images of two points of light are about $\frac{3}{1000}$ mm. apart, they both may fall on the same cone, and this would account for only one sensation being stimulated; but we also have to remember that optically the image of a point is a disc of definite size dependent on the length of focus of the lens; and if the two discs overlap, no separation would be apparent. Away from the central spot in the retina the distance apart of the objects has to be gradually increased in order to effect separation. From a study of the optics of the eye, this appears to be due to the aberration of the lens and the curvature of the surface on which the images are received. The rays become oblique and have to follow the ordinary laws which govern the definition given by such rays. It may be said that distinct vision is really confined to a circle subtending about 3°.

The lens of the eye is not an achromate, as there is no correction possible in its construction. We have only to place a piece of violet gelatine tissue against a small hole in a card and look at a luminous point. Violet, such as methyl violet, only allows the red and blue to pass, and cuts off the intermediate rays of the spectrum. In one case the red in the violet will give a sharply defined point with a blue halo round it, and in another case there will be a blue point surrounded by a red halo. The spectrum itself, when looked at from a distance, will also indicate the want of achromatism. The violet end will not be in focus when the red appears sharply defined. There are other defects in some eyes that may be encountered, and which we shall allude to in a subsequent chapter, as also the character

of the sensations which are stimulated by the impact of light on the retina.

So far, then, we have described the human eye, and this, with some slight alteration in the description, will answer for, at all events, most mammalians.

Seat of Visual Impulses.

We must next indicate where the visual impulses are originated.

If we take a candle or a lamp into a dark room in which a large piece of grey or white paper is hung on the wall, and illuminate the paper with it, holding it close by the side of the head, there will appear in the field of vision of the eye nearest the lamp an image of the blood-vessels of the retina. The light enters the eye through the cornea, and an image of the lamp or candle-flame is formed on the nasal side of the retina. The light coming from this image throws shadows of the retinal vessels on to the other parts of the retina. (This explains how it is possible to see these vessels oneself.) The same effect is seen when a second person concentrates the rays by a low-power lens on to the sclerotic coat near the cornea. The light by this plan comes to a small point on the sclerotic, and passing direct through the vitreous humour, casts a direct shadow of the vessels on to the retina.

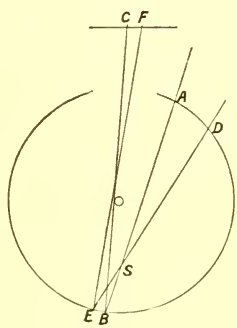


Fig. 3.

Thus, taking one vessel, S, the light when concentrated at A casts a shadow on the retina at B, which shadow is seen projected along BC. If the concentrated light is moved to D, the same vessel casts a shadow

at E, and this shadow is seen projected along EF. Knowing the nodal point of the lens and its distance from the points C and F, as seen on the screen, and the distances apart of C and F, as the other distances are also known from the diagrammatic eye (Fig. 2), it is easy to calculate the distance of S from the sensitive layer of the retina. The calculation shows the sensitive layer to be that in which lie the rods and cones—*i.e.* the retinal layer which is farthest from the lens and nearest to the black pigment layer.

This is an important fact in colour measurement, for it shows that rays of light falling on the macula lutea have to pass through the yellow pigmented layers before they reach this sensitive layer. In other words, partial absorption of violet and blue rays takes place before the sensation is stimulated in the rods and cones. In the portions of the retina outside the macula practically no absorption has to be taken into account. The reader should have this well in his mind.

The Blind Spot.

One other spot in the retina must be mentioned, viz. the blind spot. It is that spot where the retina is directly connected with the optic nerve.

The blind spot can be readily shown to exist by making on white paper two dots about 4 inches apart, fixing one eye (the other being closed) on the left-hand dot (if the right eye be used), and moving the paper to and fro from the eye. At one distance the right-hand dot will disappear, but reappears when the paper is moved nearer or farther from the eye.

Evolution of the Eye.

The eye, as described, appears to have obeyed the laws of evolution, since in the living creatures which now exist we have evidence of a primitive eye gradually becoming more perfected until we arrive at the mammalian eye.

The most primitive organ of sight, we are told, is perhaps to be found in a snail. There is apparently in it no organ of vision, and yet it feels the light. Examination shows that there is a thinning of the skin on each side of the head; and when the creature is exposed to light and darkness alternately, the movements of the body show that it has a sensation of light. Another very primitive eye is that of the nautilus. Here we have a depression in the head, shown in the right-hand figure. Its organ of vision is in fact a pin-hole camera, the pin-hole being large size. Photographs taken with such a camera would be most ill defined; and there is not complicated retinal structure which would indicate that these creatures would have any sense of colour. The objects it would see would be probably black and white, and their definition would be of the worst character.

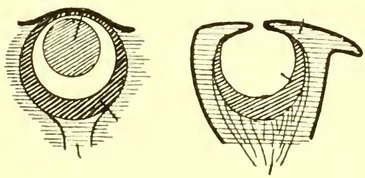


Fig. 4.

Again, we have other creatures where there is evidence of an embryo lens, which fills up the space of the pin-hole. The retinal structure is said not to be indicative of an apparatus for receiving the impression of colour. If so, we have an eye which is adapted for monochromatic vision, with definition of form far superior to that of the nautilus.

We can examine the eyes of other creatures, and can find amongst them some in which there is a better formed lens, and a rudimentary iris.

Continuing the examination, we find further improvements in the optical and retinal parts of the eye, till we arrive at that eye we have tried to describe at some length.

In our own eyes there is evidence that the colour sense has been evolved, and a very simple experiment carried out by the reader will convince him of two things—first, that the sensation of light exists quite regardless of colour, and that the two do exist together. Let us place a spot of green on a black surface either by throwing a spot of spectrum green on to a white surface in a dark room, or else let us place a green wafer on a sheet of black paper in a well-lighted room. Standing some feet away from the spot, let one eye be closed and the spot be viewed with the other eye in the ordinary manner. The green spot will be seen and the image will fall on the centre of the retina. Next turn the head and eye together, so that the image of the spot falls on a portion of the retina approaching the periphery. The image of the green spot will at a certain distance from the axis and beyond become pure white. The green colour will have disappeared entirely, and no notion of the hue would be formed if the image of the spot was thus received without having been seen on the centre of the retina.

A simple plan, and one often practised, is to mount a green or other coloured wafer on the end of a thin rod such as a long pencil, and to obtain the assistance of a second person to help in making the experiment. The experimenter fixes his eye on that of the assistant,

who holds the wafer at the distance of distinct vision and near his nose. The eye and the wafer are seen by the experimenter. The assistant gradually moves the wafer away from the nose towards the right or the left. The experimenter keeps his eye fixed on that of the assistant, and at some angle which the line joining the wafer and the experimenter's eye makes with the line joining the eyes of the two parties, the wafer appears colourless. The angle made is often guessed.

The disappearance of colour from wafers of other hues can be noticed in the same way. It must be stated here, though it will be restated farther on, that the brightness of the colour and the size of spot cause variations of the angle at which the colour disappears. In fact, if the brightness be feeble and the angle which the coloured disc subtends on the retina be very small, a shift in the axis of the eye of a very few degrees will suffice to render the spot colourless.

This simple experiment is well worth consideration, as it shows that the retina is most sensitive to colour round the part which the axis of the eye cuts, and that it gradually diminishes in sensitiveness to colour, though not necessarily to light, as the periphery is approached. This is exactly what one would expect if the eye has obeyed the laws of evolution, and it has to be reckoned with in certain measurements of colour which are to be described. It may be stated here that every individual is colour blind, though not light blind, in the outer part of the retina. The most difficult colour to cause to disappear is the blue, and it gives us the hint as to which colour was the first to be evolved. The sensation of light is shown to be white, and colour has been

added on to the sensation, or a portion of that sensation has been converted into colour. We shall see farther on that apparently there are three distinct visual colour apparatus and that *light* is the fundamental sensation of each colour sensation.

CHAPTER III

ON PHENOMENA IN VISION

It may be as well to mention briefly some facts connected with the visual effects of the impacts of light, coloured or otherwise, on the retina, which occur and are often overlooked. Those given here are taken from the late Mr. Shelford Bidwell's papers, printed in full in *Nature* and in the *Proceedings of the Royal Society.* They are also epitomised in a small book called *Curiosities of Light and Sight.*[1] He brought together and expanded some of Charpentier's admirable work, adding his own experiments, and giving explanations of phenomena which appeared to require elucidation.

Recurrent Vision.

When a flash of white light is received on the retina, we have what are called positive recurrent optic images. Bidwell tells us that they were first accidentally discovered by Professor W. Young, when experimenting with a large electrical machine. Young noticed that after a strong spark had illuminated any conspicuous object, it was seen at least twice, the second time after an interval slightly less than a quarter of a second after the first—the first image was vivid, the second faint. Often it was seen a third time, and sometimes even a fourth time. This phenomenon he called "recurrent

[1] Messrs. Allen & Co., to whom we are indebted for permission to use the illustrations in this chapter.

vision." Bidwell gave it the name of the Young effect. Let one pole of an influence electrical machine be connected with the inner coating of a half-pint Leyden jar and the other with the outer coating, and the discharging balls be placed one-quarter inch apart, and a white object such as a small sheet of paper be placed in an upright position a few inches away from the terminals of the machine, and then the machine be worked till the discharge takes place, the room being darkened. If the eyes are screened from the sparks and are directed towards the white object, the object will be seen, and in about one-fifth of a second a recurrent image will make its appearance, and after another interval of darkness a second faint one will often be seen. Bidwell says that under favourable conditions he has observed as many as six or seven reappearances of an object illuminated by a single discharge. It must be recollected that the light of a discharge is excessively intense, and that owing to its very short duration the retina does not fully realise how intense it is.

The Ghost.

This recurrent image can be well shown to an audience on a screen by one of Bidwell's many devices. A metal disc of some $2\frac{1}{2}$ inches diameter, which can be turned about its centre, is prepared and placed in position as a lantern slide. A small circular hole is drilled near the periphery. When the disc is focused on the screen, we have, of course, a dark image of the black disc, but a small spot of white light near the rim. When the disc is slowly rotated so that the spot travels round the screen with merely a slight elongation in the line of its travel, if the eyes be kept

steadily fixed on the screen, it will be found that a faint violet spot travels behind the white oval, separated by an interval of darkness. When the speed of rotation is increased, the interval between the two spots will increase, and when the rotation begins to stop the two spots come nearer to one another, and finally the two merge into one another. If a green glass be placed in the beam, the violet of the ghost of the green spot will become apparently more intense. With orange glass the intensity of the violet becomes less; whilst if the light be made red, there will be no ghost to the red spot.

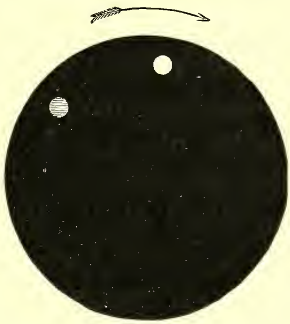


Fig. 5.

Bidwell made an apparatus by which he could repeat this experiment with a spectrum colour, and found that the one colour which gave no ghost was the red. When the whole spectrum, as a line, was rotated, the ghost to each colour, except the red, was violet. The time of rotation being known, and the interval between the original spot and the ghost being measured, we have the means of calculating the interval that elapses between the first image and that caused by recurrent vision, which Bidwell puts down as closely one-fifth of a second. The interval of time which elapses between the two images seems to be the same for all colours. If there were a difference this accurate observer would have noted it.

Charpentier's Law.

Charpentier, the eminent French scientist, made many observations on the impressions received on the

retina by light. Charpentier's law, Bidwell tells us, is this: "When darkness is succeeded by light, the stimulus which the retina first receives, and which causes the sensation of luminosity, is followed by a brief period of insensibility, resulting in the sensation of momentary darkness. It appears that the dark period begins about one-sixtieth of a second after the light has first been admitted to the eye, and lasts for about an equal time. The whole alternation from light to darkness and back again to light is performed so rapidly that, except under certain conditions, which, however, occur frequently enough, it cannot be detected."

The apparatus which Charpentier employed for demonstrating and measuring the duration of this effect is very simple.

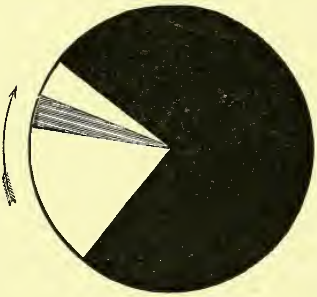


Fig. 6.

"It consists of a blackened disc with a white sector mounted upon an axis. When the disc is illuminated by sunlight and turned rather slowly, the direction of the gaze being fixed upon the centre, there appears upon the white sector, close behind its leading edge, a narrow but quite conspicuous dark band. The portion of the retina which at any moment is apparently occupied by the dark band, is that upon which the light, reflected by the leading edge of the white sector, impinged one-sixtieth of a second previously."

Bidwell, with a 4-inch disc of black having a slit of about one-fiftieth of an inch wide at the circumference, placed in front of an illuminated ground glass, was able to show more of these dark periods. When the eyes were fixed on the centre, and the revolution of the disc

was about once a second, the disc presented an appearance as given in the figure. He says that the Charpentier effect occurs at the beginning of the period of illumination, and a dark reaction at the end of the period of illumination. He also explains and shows that owing to what is called the proper light of the retina, or what we call the intrinsic light, ordinary darkness is not an absolute black, and says that the darkness which is experienced after the extinction of a light is for a small fraction of a second more intense than common darkness. He describes experiments to show this abnormal blackness. Finally, he gives a diagram of the different effects on the retina

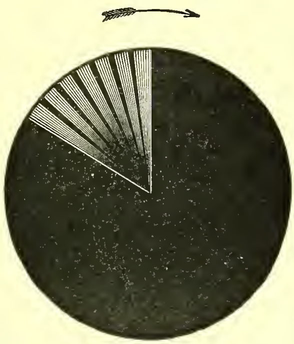


Fig. 7.

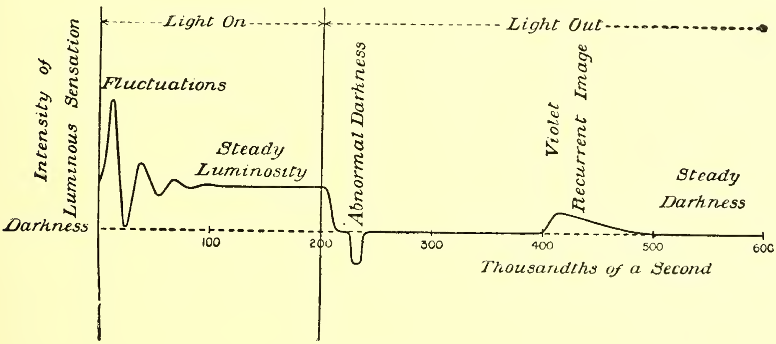


Fig. 8.

during the continuance of light and after it is cut off, till the first recurrent image is seen. One may presume that to the next recurrent image the darkness is steady, and is that of the intrinsic light of the retina.

Coloured Borders to Black Lines.

There is another phenomenon connected with the visual effects which ought to be noticed, of which the origin has been traced by Bidwell. It is not uncommon for a reader to go to sleep with a book in his hands. He may wake suddenly and turn his eyes at once to his book, when he will find that the printed matter instead of being black becomes red, and it is only after several seconds that the black of the printed matter is seen.

Amongst various other phenomena, Shelford Bidwell traced the cause of this one, and communicated his observation to the Royal Society[1] in 1896 and 1897, and the following description is abstracted from his communication. After several preliminary experiments, he describes one in which a white card disc with a diameter of 6 inches was employed. A sector of 60° was cut out, and the remainder of the disc was divided into two equal parts by a straight line from the centre to the circumference, and one of these parts was painted black. The disc was attached to a horizontal spindle, and was rotated five or six revolutions per second, whilst its front was illuminated by a lamp of sixteen-candle power. A white card, on which was a black line or design composed of black lines was supported behind the disc, and viewed intermittently through the open sector. When the rotation was such that the open sector succeeded the black part of the disc, and was then succeeded by the white portion, the black lines were received as red.

When other experiments were carried out, it was found that a bluish-green border became visible when the illumination was increased, and that with a still

[1] *Proceedings of the Royal Society*, vols. lx. and lxi.

stronger illumination the red was entirely replaced by the greenish blue. It may be stated that if the lines are wider than about $\frac{1}{25}$ of an inch, when observed at a distance of 2 or 3 feet, as the thickness increases, a black central line is seen bordered in red, the borders lying in the black. It is only when the lines are thinned down that the coloured borders meet and cover the whole of the lines.

When the sector was rotated, so that the black part followed the aperture, there was no suspicion of red, the lines appeared to become blue. This appearance, Bidwell states, is partly if not altogether illusory. It is the bright ground in the immediate neighbourhood of the lines that becomes blue, the lines themselves, except possibly just within the extreme edges, become grey, owing to the alternation of black and white. When a small card was placed behind the rotating disc, it merely turned a grey, without any suspicion of blue in it. From other experiments, Bidwell appears to show conclusively that the red effect on the black lines is due to a spreading sympathetic action for a short interval of the red-perceiving apparatus, when the retina receives the impact of white light after a period of darkness, and that coloured light in which no red was present gave no colour to the lines. The green-blue lines which succeed the red when strong illumination is given to the card is the after-image of the red (see Chapter XXIII.). The blue border outside the lines, which is seen when the aperture succeeds to the white, is probably the after-effect of the red. We thus see that in considering the effects of light on the retina, account has to be taken of its duration and of the state of sensitiveness due to darkness.

Benham's Top.

One of the objects of Bidwell's investigations was to account for the colour phenomena which are produced in Benham's spectrum top. The figure below gives the idea of the top, which is a disc of about the size of the figure.

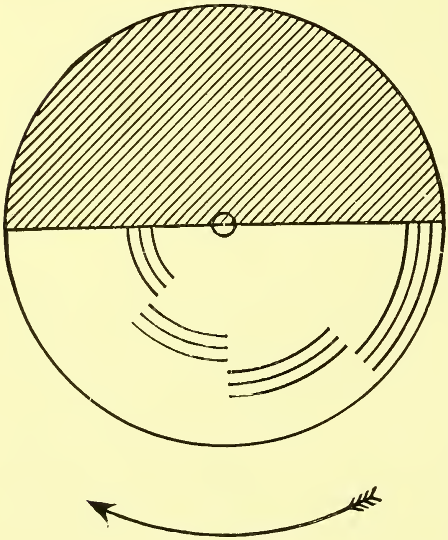


Fig. 9.

When the disc is rotated rather slowly round its centre, each group of black lines will probably appear of a different colour. The hue depends on the speed of rotation and on the brightness of the light. The maker of the top says that when the top is rotated in the direction of the arrow the outside set of lines will appear red and the inside one dark blue, whilst the intermediate lines will show a green colour. It will be noticed that the rotation gives black first, then the outside lines on a white ground, then the second and third set sandwiched in between the outside and inside lines, which latter end in the black background. On quiet rotation the lines appear as above, and it will be seen that Bidwell's experiments confirm the idea that the red of the outside lines is due to a spreading of the red sensation excited by the white to neighbouring portions of the retina, on which the lines are received. If the

lines are made thick, the red borders are seen alongside a black central space. The blue seen in the inside lines apparently is a mixture of the black background and of the green-blue band which is seen when a straight or curved edge of a white surface is darkened (p. 27). Such an edge shows a blue-green border for about one-fifth of a second, owing to "a sympathetic insensitive reaction" in the receiving apparatus outside the image. The writer made experiments with this same top, illuminating it with the white arc light and with monochromatic patches of light, and several observers gave the same descriptions of what they saw when the disc rotated before them. Calling the outside set of lines No. 1, the next No. 2, the next No. 3, and the innermost No. 4, when the rotation caused the lines to affect the retina after a period of rest by the black, the effect produced by moderately luminous white was—

No. 1, crimson,
No. 2, olive green,
No. 3, grey (slightly violet),
No. 4, dark violet.

When the illumination was by red light (C of the spectrum)—

No. 1 was red,
No. 2 was lighter red,
No. 3 was very light olive green,
No. 4 was darker olive green.

In this light no other sensation but red and a very little green was in the colour used, which probably accounts for the colours in Nos. 3 and 4, for when the

red was that of the lithium hue, in which there is only the red sensation stimulated—

Nos. 1, 2, 3, and 4 all were red.

When a green light close to the green magnesium line of the spectrum was the illuminating colour—

No. 1 was bluish green,
No. 2 was lighter bluish green,
No. 3 was same as No. 2,
No. 4 was ruddy black.

In this colour the constituents may be said to be the green sensation and white (see Chapter XV.).

When the blue of the blue lithium hue was the illuminant—

No. 1 was grass green,
No. 2 was lighter grass green,
No. 3 was same as No. 2,
No. 4 was ruddy black.

In this case we have the blue sensation mixed with a large quantity of white (see Chapter XV.).

When the illuminant was the whole of the violet of the spectrum—

Nos. 1, 2, and 3 appeared light violet, and
No. 4 darker violet.

In the case of the violet there are only the red and blue sensations present (see p. 240).

The two next experiments are interesting, as the illumination was with white light, but the white was compounded of two rays only, two slits being opened in the spectrum and white matched.

The illuminant was the white of a mixture of red and bluish green :—

No. 1 was indigo blue,
No. 2 was reddish orange,
No. 3 was same as No. 2,
No. 4 was darker orange.

The next illuminant was the white of a mixture of spectral yellow and blue :—

No. 1 was sky blue,
No. 2 was sage green,
No. 3 was same as No. 2,
No. 4 was bluish black (perhaps black).

These phenomena are explained if we take it that each sensation has its own sympathetic action on the sensation-receiving apparatus, that of the red being greatest and that of the blue least.

Some experiments recorded in *Nature* by Finnigan and Moore with broad lines fully bear out Bidwell's contention as to the colours seen in the lines when illuminated by the arc light. They made the lines a centimetre broad and found that on rotation the band following the black was bordered with a red over the black, and on that which came from *white to black* the band was bordered on the white with a blue to green colour, leaving the band quite black. Bidwell's explanation, as before said, is that the red colour of the fine lines following the black are due to sympathetic spreading of the red sensation, whilst the blue colour of the fine lines following the white is due to the want of such sympathetic action when the illumination is rapidly shut off, leaving the other sensations exhibited on the black surface on which those lines are practi-

cally viewed, and which the retina takes as part of the lines, though the colour is outside their border.

When the speed of rotation of the disc is gradually increased, the red of the outer lines grows darker and duller, and then, passing through a transition, which Messrs. Finnigan and Moore were unable to observe, the lines assumed a vivid green, then a blue, and when the rotation was very rapid they assumed a violet hue.

In regard to Benham's top, it has been stated that the colour phenomena were due to the want of achromatism in the eye. Mr. Bidwell conclusively showed that it was not.

Fig. 10.

He quotes an experiment which is fatal to the theory. He prepared a disc as above, and spun it above a page of printing. The letters beneath that part of the disc that is partly white and partly black will appear red, but those beneath the remainder will always appear black. As he remarks: "The demarcation is quite definite, and a single printed word may be made to appear red in the middle and black at its two ends." It is, of course, impossible that the lenses of the eyes should be perfectly accommodated for the letters which appear black, and, at the same time, seriously out of focus for the others.

CHAPTER IV

COLOUR PATCH APPARATUS

Colours which we see round us are almost invariably impure colours—that is, colours which on analysis are found to be composed of mixtures of pure colours, or to be pure colours mixed with white. Thus the yellow of the marigold, which is a brilliant orange yellow, although it appears to be a pure saturated colour, is found to be composed of all the spectrum colours, from red to yellow-green, which have certain relative brightnesses to one another which differ from those found in white light. It is proposed in this chapter to describe an apparatus which can be used for the *quantitative* measurement of brightness and of certain qualities which the spectrum colours possess, and at the same time to show that it is equally useful for the measurement and analysis of colours which are seen in such objects as the marigold. With this purpose in view, we must have an apparatus which, when applied to the spectrum, shall not only be able to isolate a slice of colour from the spectrum by a slit placed in it, but also to produce a patch, at least $1\frac{1}{2}$ inch square, of the colour which passes through the slit or a mixture of the colours which pass through more than one slit.

It would be foreign to our purpose if we described in detail the spectroscope as ordinarily used. It is supposed that the reader is familiar with its principles, and any description that may be given here will only be

such as is necessary to understand the lines on which the "colour patch apparatus" was designed.[1]

Collimator.

In the spectroscope, which is dependent on prisms for the dispersion of light, there is a slit at one end of a tube with a lens at the other end, to render the rays coming through the slit parallel. The lens is therefore of such a focal length that the slit is at its equivalent focus. The slit, tube, and lens form what is called the collimator. The slit can be closed or opened by a screw arrangement; and here it should be remarked that for exactness of measures the *jaws of the slit should both move* through equal distances outwards or inwards, so that the line of junction of the jaws when closed should always be the central line of any aperture to which the slit is opened. The necessity of this will be apparent when it is called to mind that every colour in the spectrum, when focused, is an image of the slit, and that the central line of the slit is the centre of the coloured image. Should one of the jaws be fixed whilst the other is movable, the centre line of the slit moves from the line of junction when the slits are closed through half the width of the slit, and this entails a corresponding movement of the coloured image of the slit. As the rays of the light falling on the slit emerge from the lens as parallel rays, they will fall on the surface of the first prism as parallel rays, and all the rays of each colour will have the same deviation as they pass through it, and through as many prisms as are placed in its path. The deviation alters in amount according to the angle at which the surface of the prism is placed in

[1] See Papers Nos. 4, 5, and 6.

reference to the axis of the parallel beam. For convenience' sake, it is better to have the surfaces of the prisms so placed that the central ray of the spectrum (say), the blue-green, shall have what is called "minimum deviation."

This angle of minimum deviation is readily found by throwing a defined spectrum formed by one of the prisms on a screen. The ray selected is watched whilst the prism is turned on its base right and left. One position will be found where the selected ray seems to have no movement; though turning it either to right or left, the ray will commence to travel along the screen in the same direction. The angle, when the motion ceases, is the angle sought for. It must be remembered that each ray has its own angle of minimum deviation, and the blue-green ray is chosen for convenience, as dividing the spectrum into fairly equal parts. When the first prism has been fixed, a second and a third may be placed in the path of the beam, and the angle of minimum deviation found with the added prisms in the same way. Care must be taken that the slit is parallel to the edges of the prism, otherwise a vertical line of colour in the spectrum may not be of the same hue throughout.[1] The surfaces of the prisms should be accurately vertical, and usually this can be done by levelling the bases. Our own prisms are very colourless and made of medium flint-glass. Two of such prisms give a dispersion which is quite sufficient to form a spectrum some $3\frac{1}{2}$ inches long. The "angle" of the medium flint prisms we use is $62\frac{1}{2}°$, their height $1\frac{1}{2}$ inch, and the width of face 2 inches.

The collimator tube is for steadiness supported on a stand of nearly its own length, and rests on two V's.

[1] There is always a very slight curvature of bright lines in the spectrum.

The collimator and prisms are each supported separately, the former being rigidly fixed, so that there is no "spring" to it (which is not usually the case in spectroscopes found in a chemical laboratory). It is most important that a collimator should be rigidly fixed in regard to the surface of the prism.

The prisms are mounted on separate brass bases with levelling screws, to secure that their faces can be made truly vertical; and when the angle of minimum deviation for the central ray has been found, the brass levelling screws find a bearing in the brass plate below, in which depressions are made in positions corresponding to this angle.

For forming an image of the spectrum an achromatic lens of 30-in. focus is employed. It is mounted on a camera which has a rack and pinion focusing arrangement. The focusing screen has a *horizontal* swing-back, which allows one end of the spectrum to be at a longer focal distance than the other. This is necessary, as the focal distance from the lens for the violet is shorter than that of the green, and still shorter than that of the red. There is the usual ground-glass screen for focusing, and grooves which take dark slides holding plates $6\frac{1}{2}$ by $3\frac{1}{4}$ inches. The instrument as now described is a photographic spectroscopic apparatus.

Slide in the Spectrum.

In place of a photographic plate, the grooves will take a metal or wooden slide, in which is inserted a brass panel and slits, as will be found described farther on (p. 41).

If we remove both ground-glass and slide, and, a short distance in front of the position where the spec-

trum is in focus, place a lens of some $4\frac{1}{2}$ to 6 inches in diameter and having a focal length of about 3 feet, a white image of the face of the first surface of the first prism can be obtained on a screen some 4 to 5 feet distant from the focusing screen. The lens recombines the whole of the spectrum if its axis makes a slight angle with the direction of the central ray.

We can apply the optical formula $F=\frac{ff^1}{f+f^1-s}$, where F is the focal length of the combination of the lenses which form the spectrum and the "collecting" lens. Let the rays f^1 and f, the two focal lengths, be 30 and 36 inches respectively, and s (the separation of the lenses), about 36 inches, we find that the focal length F is 3 feet and the optical centre is about half-way between the two lenses, or $1\frac{1}{2}$ foot from the first lens. The first surface of the first prism may be taken to be 2 feet away from the optical centre, so that the sharp image of the surface of the prism will be about 6 feet from the optical centre, or 4 to 6 feet from the combining lens. If the axes of the two lenses lay in a straight line, the image would be bounded by fringes of colour, but by causing the axis of the combining lens to make a slight angle with that of the first lens, the fringes can be made to disappear. If now the wooden slide, with a slit located in the brass fitting, be passed through the spectrum, the image of the surface of the prism will be found to be of the colour which passes through the slit, so that a monochromatic patch of light of any colour can be thrown on the screen. Instead of a screen, it is convenient to have a cube covered with white material mounted on a rod and backed by black velvet, on which the patches shall fall. This isolates the patch, and the colour is backed by a black ground. Even if the slit on the spectrum be

opened wide, the colour will still be practically monochromatic, since it is found that the rays on each side of the central ray passing through the slit, when combined, match it in colour. If the recombining lens be removed, there will still be coloured patches showing on the screen, but as the slit is moved from red to violet there will be a continuous travelling of the patches along the screen. The recombining lens keeps the patches in the same place.

Single Colour Patch Apparatus.

The above general remarks show on what principle the colour patch apparatus was constructed, and the next figure shows it as it at present exists.

In this apparatus only one colour patch can be formed. The rays R, R, coming from the crater of the positive pole of the electric light, are collected by a lens L_1, and an image of the crater thrown on the slit S_1. After passing through the collimator C, the rays emerge as parallel rays; part passes through the prisms P_1 and P_2, and is collected by a lens, L_3, of about 30-inch focal length, and a spectrum is formed on a focusing screen at D, which is removed, and a slide inserted in which slits can be placed. The image of the surface of the first prism is formed on the white surface of a cube, E, by means of the lens L_4 (of about 30-inch focal length), so arranged that the image of one edge of the prism falls at *a*, the other edge falling outside *d*. Part of the beam which passes through the collimator is reflected from the surface of the first prism to a mirror G^{I}, and passes through a lens, L_5, then through a bundle of glass, G^{II},[1] placed at an angle to the beam, and on to the surface

[1] For ordinary work the bundle of glasses G^{II} is not required, which does away with the mirror G^{III} and the sector M^{II}.

dc of the cube, a rod, K_1, being placed in its path, to secure that this white beam does not fall on *ad*, on which the colour mixture falls. The portion of the beam which is reflected from G^{II} is again reflected by

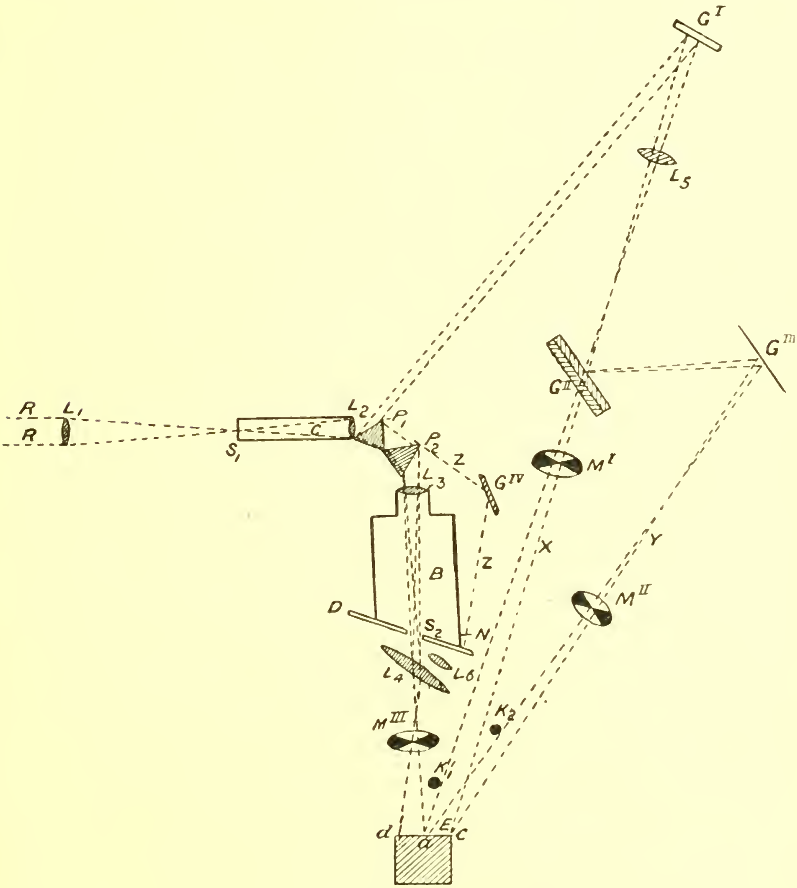


Fig. 11.

G^{III}, a silvered mirror, on to *cd*, a rod, K_2, placed in its path prevents it falling on *ad* or *ac* as desired. In all three beams, sectors, M^I, M^{II}, and M^{III}, can be placed, to allow any or all to be reduced in intensity at pleasure. In the beams X and Y any absorbing medium desired can

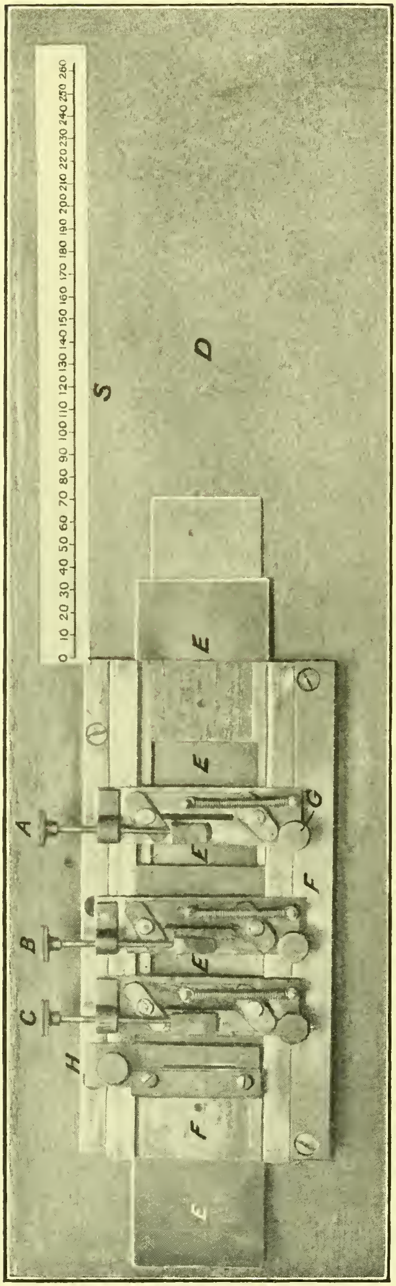


FIG. 12.

be placed. A small ray of light, Z, is allowed to pass beyond P_2, and falls on a small mirror, G^{IV}, which reflects it on to the back of D, casting a shadow of a needle, N (fixed to B, the camera), on a scale at the back of D.[1]

L_6 is a lens of short focus which can be moved into a fixed position behind L_4 to throw an enlarged image of the slit on a scale placed above *dc*.

Slits and Slit Holder.

There is one part of the apparatus which must be shown in some detail, viz. the slide D and the slit holder. The slide D is shown in the annexed figure.

In Fig. 12 F is a brass plate with necessary

[1] In the writer's present apparatus the needle is done away with and a transparent scale is mounted in the top of D, and a small lens in front of the scale throws a magnified image of the graduation on a distant screen. (See the description of the modified apparatus, p. 45, for details.)

grooves cut in it (see Fig. 13). A, B, and C are three slits which can be clamped in any position by means of the screw GG. H is a slit which is always kept in one position and has a fixed and carefully measured opening (used for measures to be compared together from time to time). (There is a transparent scale S fitted into D, through which a beam of light passes on to a distant screen with a mark on it; see p. 45.) XX are two grooves cut the whole length of the top and bottom bars, as also are YY. In XX the slits (of which a full-size figure of one is shown in Fig. 14) slide along XX and thin black cards EE in YY, Fig. 12.

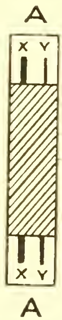


FIG. 13.

The slits in the brass frame, it will be seen, are made to open centrally, so that the centre line of any aperture is always in one position.

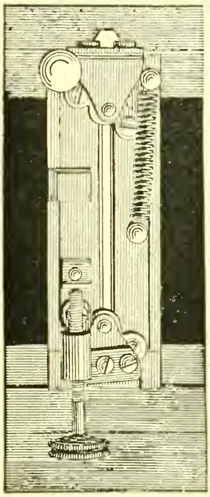


FIG. 14.

The brass frame F is fixed to a hard-wood slide D (in which there is a rather smaller opening than the dimensions of the brass plate).

This apparatus is all that is, as a rule, required for colour measurement and mixture.

[It may here be noted that by removing the slide at D, and then placing a lens of 9- or 10-inch focus some 4 inches in front of the recombining lens, an enlarged spectrum can be obtained on a white screen placed at the same distance as the cube.]

The lens L^1, which throws an image of the crater of the arc, should have such a focal length that the length of the slit is well covered by the brightest part.

It should also be of such a diameter that the ratio of diameter to focal length is not less than the ratio of the diameter of the collimating lens to its focal length. If it be less, the collimating lens will not be filled with light. [It should be noted that the smaller the ratio of focal length to diameter of the collimating lens the brighter will be the spectrum.] If Fig. 11 be examined, it will be seen that any variation in the brightness of the spectrum is accompanied by a corresponding variation in the light reflected from the first surface of the prism. This is a most valuable property, as the brightness of any colour is most frequently referred to in terms of the brightness of the reflected white beam.

Apparatus for using two Spectra simultaneously.

A later form of colour patch apparatus[1] is arranged to enable two spectra formed by the same source of light to be used either separately or together. This arrangement allows a comparison of any differing mixtures of spectrum colours to be made, and it also allows the addition of any desired quantity of white light to the colour patches formed by the aid of either of the two spectra.

In this apparatus, as in the last, the intensity of the white light used for comparison with the colours varies with the intensity of the spectrum. The same white light is used as before to form the spectrum and the reflected white light as the comparison light, but, in addition, the main light, after passing through the two prisms, passes through a half-silvered mirror, inclined at about 45° to the axis of the lens. The rays reflected are again reflected so as to pursue a course roughly parallel

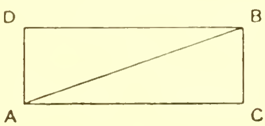
[1] See Paper No. 6.

to the main spectrum. Thus two similar spectra are placed side by side. The accompanying diagram will show the arrangement.

As in the apparatus described, E is the source of light used outside a darkened room, L_1, L_2 are lenses throwing an image of the source of light on the slit S_1 of the collimator C. The parallel beam passes through the prisms P_1, P_2 and is received on a colour-corrected photographic lens, L_4, of sufficient diameter to take in the whole of the light coming through the prisms.

The lens forms a spectrum on a focusing screen at D_1, which can be removed and slits S_2 placed in the image. L_6 collects the colours and gives an image of the face of the prism P_1 on the screen B.

Behind the lens L_4 is placed the semi-silvered mirror M_1, reflecting, as nearly as may be, the same amount of light as is transmitted through it. If the mirror be on a plate of glass with parallel sides, it should be as thin as possible, to avoid any serious mixture of colour in the second spectrum due to the reflection of the unsilvered surface. If a plate be made up of two thin prisms, as in margin, with the surface AB of one of them half silvered, the transmitted beam is not deviated, and the beams reflected from DB and AC[1] are diverted and not used.



The reflection from the semi-silvered mirror M_1 falls on a silvered mirror, M_2, which reflects the beam in such a direction that it falls on B, the image of the spectrum being thrown on D_2. The image of P_1 is thrown on B by the lens L_5. A beam of white light is reflected from

[1] The two thin prisms are used in order to protect the silvered surface. One thin prism by itself may be employed, but the length of the direct spectrum will be slightly increased or diminished according to the position of the thin end of the wedge.

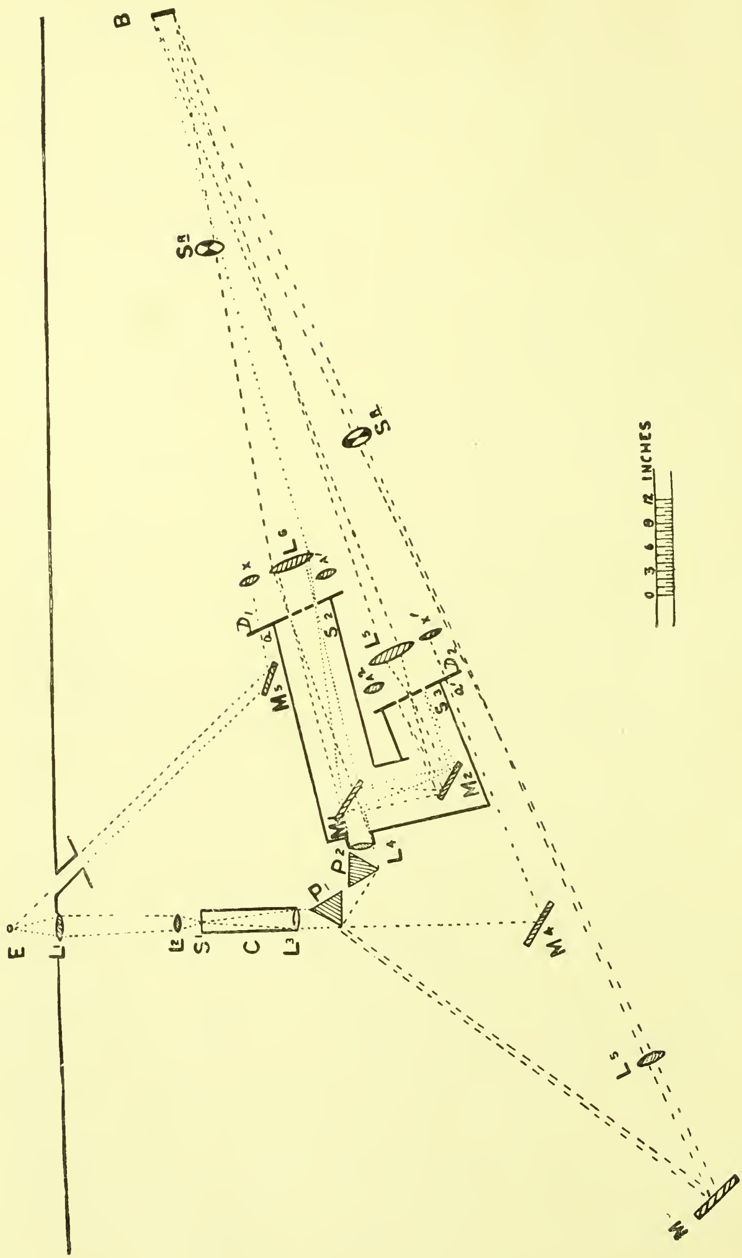


FIG. 15.

the face of P_1 by M_3 (which may be either a silvered mirror or plain), and is also focused on B, so that we have the patches from both spectra and from the white light falling over one another on B. By means of rods correctly placed, a colour or colours from either spectrum can be isolated and be mixed with any proportion of white by using sectors as shown. There are slides carrying the slits at D_1 and D_2, and to them are attached transparent scales. In the case of D_1 a beam of white light falls on the mirror M_5, as shown, and passes through the transparent scale at a, and a lens X throws a magnified image of the graduation on a distant white screen, on which a zero mark is drawn. This enables the transparent half-millimetre scale to be read to a tenth of that unit. In a similar way the scale at a' is magnified by X′ by a beam of light falling on M_4. When the scale readings are not required, the sources of light illuminating them are covered up.

Again the lenses A^1 and A^2 are mounted in a sliding arrangement and can be moved in front of lenses L_5 and L_6. When a slit is drawn in front of A^1 or A^2 the image of the aperture is magnified on a distant screen, carrying a scale, and the width of the slits can be accurately ascertained by noting on such scale the reading of the breadth (say) of $\frac{1}{2}$ millimetre width of slit.

Still more recently the apparatus has been altered in one particular. The half-silvered mirror M is replaced by a fully silvered mirror or a right-angled prism, which reaches to half the height of the prism. The bottom half of the beam is totally reflected to M_2, and a spectrum is as before formed at D_2. On reaching the screen B, each patch is half the height of the full patch. By this means any difficulty about half-silvering is avoided, the slight second spectrum which overlaps the main spectrum

from the reflection from the back of the semi-silvered mirror of plane glass is entirely absent. Further, the two spectra are very nearly equally bright.

The Receiving Surface.

In early experiments that were made, white cardboard was used as a receiving screen, and for ordinary work answers well; but the question arose as to whether card of the same kind of whiteness could always be obtained. This led to the conclusion that a white of definite "whiteness" ought to be used. A trial with various samples of zinc oxide showed that it might be relied upon as a white which could always be reproduced and one which could be readily obtained. The zinc white should be mixed with a very pure white gelatine or isinglass, which is dissolved in hot water. The gelatine solution is used very sparingly, only sufficient being added to cause the oxide to adhere to the card on which it is coated. On comparing the intensity of the spectrum colours reflected from ordinary card and the card treated with the oxide, it was found that with the former there was a slight deficiency in the blue and violet, and also a little in the green as compared with the former. A card or board should be brushed over with a cream of the oxide and be allowed to dry, when another coat should be given it, and then be flatted down with a brush when set. An ordinary white card placed alongside will appear yellowish. There should not be the *slightest gloss* on the oxide; it should appear quite matt if the surface be properly prepared. Another good receiving surface is plaster of paris which has been set on a fine ground-glass surface. It is such a surface that Mr. Lovibond uses with his tintometer.

On the whole, we prefer the zinc oxide surface.

When using the colour patch it is essential that a definite surface only should be illuminated, and we have found that if the face of one side of a cube be covered with the prepared white card and behind it black velvet be hung, we have an ideal screen on which to receive the colour or white or both. A three-sided prism of equi-angular section would perhaps be better, as then there is no danger of the sides of the cube being in any degree illuminated, which might be the case when the screen surface is not absolutely perpendicular to the light falling on it.

The annexed figure shows the arrangement in use. A, B, C, D, E, F are made by dovetailing two boards at right angles to one another. These are covered with black velvet. A scale, K, which is used for measuring the width of the slits in the spectrum, is fixed as shown. The cube H is mounted on a stand such as are found in all chemical laboratories, and the iron rod passes through a hole bored in its centre. The cube can be lowered or raised by unloosing the screw I, and any surface can be presented to the light by twisting it round on the rod. There is room on the board C, D, E, F for a rod to be placed for casting the necessary shadows on the face of the cube. In some cases a surface of flat card (coated

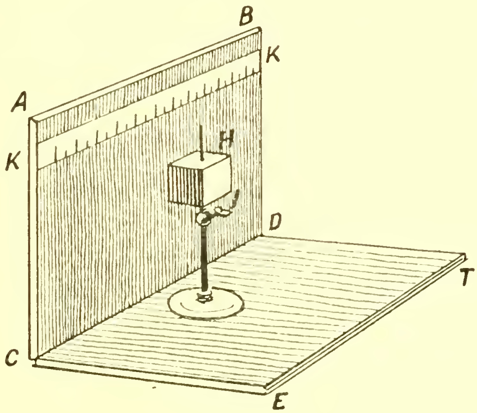


Fig. 16.

with the oxide) has to be employed. A square of the requisite size is cut out in matt-black paper and fixed over it by drawing pins. This plan is not so satisfactory as that described, as the black paper is always to some extent illuminated, and as it is in juxtaposition to the white surface it is sometimes puzzling. When the velvet background is used, it receives the light, but is very little illuminated, and any small illumination there may be is not viewed on the same plane as the white or coloured patch. We have given these minute details, for exactitude in colour measures very largely depends on attention to such minutiæ.

Other white surfaces can be made by pressing magnesium carbonate in an hydraulic press so as to give a flat disc, which can be cut into any desired shape. The surface does not appear to be quite so matt as that of the zinc white.

Scaling the Spectrum.

The method of "scaling" the spectrum is as follows. As is well known, metals can be vaporised by the arc and show "bright-line" spectra. Thus the vapour of lithium shows a good many lines when its spectrum is examined on the screen. There are, however, two specially bright, one in the red and the other in the blue of the spectrum. Through the aperture of the slit which is being used for forming the patches these lines are successively caused to pass and their centres made to coincide with that of the slit aperture. The scale numbers for these lines are noted. If sodium and magnesium are also volatilised, other lines of known wave-length can be passed through the slits and the scale numbers read as before. This enables the scale numbers of the different Fraunhofer lines to be calcu-

lated, and the spectrum will then be "scaled," and the colours passing through the slit for any scale number will be known. The following is a table of wave-lengths for the different Fraunhofer lines and for the lithium lines:—

Fraunhofer and Bright Lines.	Colour in Bright Spectrum.	λ Wave-Length.	Scale Number adopted in the book.
A . . .	Dark red	7594	...
B . . .	,,	6867	61·3
Li . . .	Red	6705	59·8
C . . .	Scarlet	6562	58·1
Na . . . / D . . .	Orange / Yellow	5892	50·6
E . . .	Green	5269	39·8
bM$_{g}$ . .	,,	5183	37·7
F . . .	Blue-green	4861	30·05
Li . . .	Blue	4603	22·8
G . . .	Violet	4307	11·2
H . . .	Dark Violet	3968	5·5

The visible spectrum is divided by these lines fairly equally along its total length. The difference in these scale numbers by no means corresponds with the difference in wave-length. If it be required to know the wave-length of any scale number, it can be ascertained with great accuracy by calculation. The squares of the reciprocals of wave-length $\left(\frac{1}{\lambda^2}\right)$ will lie very closely in a straight line if the scale numbers are used as abscissæ. [It is useful to have a chart made on a large scale and to read off the wave-lengths from the curve.]

The Production of Images in Monochromatic Light.

The colour patch apparatus has a further use,[1] which arises from the fact that on the screen we have a patch

[1] See Paper No. 18.

of white light which is the image of the first surface of the first prism. If, then, we can by any means form an image of an object on the first surface of the prism, and then pass a slit along the spectrum, we shall have its image on the screen in the same monochromatic light as that which is issuing from the slit. For the purpose in view, a single large prism is substituted for the two prisms shown in Fig. 11, and a long collimator with lens of a sufficient diameter to fill the prism.

FIG. 18. FIG. 19.

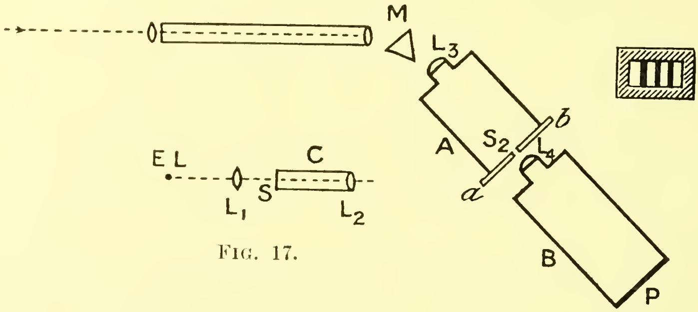


FIG. 17.

The accompanying figures will indicate the arrangement. To show, for instance, the poles of the electric light in monochrome on the screen, they were so placed that a beam of light passed through the slit S of the collimator on to the centre of the collimating lens L_2 (Fig. 17). A convex lens L_1, of nearly the same focus as L_2, was placed in the path of the rays, and so adjusted that a real image of the poles was formed on L_2. These passed through the lens L_2 as nearly parallel rays, and as such fell upon the prism, and then passed through the remainder of the apparatus as sketched in Fig. 18, where M is the prism. L_3 is a lens to bring the rays to a focus as a spectrum on *ab* after passing through a camera, A. L_4 is a lens, shown in the figure as connected with a

camera, B, which brings the image of the prism and the bright image cast on it to a focus at P. By placing a slit, S_2, in the spectrum, the image cast on P will be in monochromatic light (that coming through the slit). L_1 should be of such a focal length that it should be as near the slit as possible. With this arrangement it is very curious to watch the variations in the brightness of the arc and of the flame which accompanies the movement of the slit through the spectrum, and as each variation can be photographed on a polychromatic photographic plate, we can obtain records of all that is occurring (see Fig. 21). Further, by placing strips (Fig. 19) of spectacle lenses (cut at suitable distances from their centres) in front of other slits in the spectrum, images of various colours can be made to fall on P (Fig. 18). Incidentally, it may be mentioned that investigations as to the cause of the variable nature of different flames can be carried out by this plan.

To obtain an image of the sun in monochrome, a long collimator appears to be a necessity, but the aperture need not be large. Suppose we determine to have an image of the sun on P (Fig. 18) of 2 in. diameter, the image on M need not be more than 1 in. at most. For this purpose we must have a collimator 10 ft. long. Two lenses of this focal length can be fixed one at each end, and a slit in front of that lens which is presented to the sun's rays. The arrangements followed will be the same as those given for the electric light. There appears no difficulty in producing a monochromatic image of almost any size if the collimator be sufficiently long and the face of the prism sufficiently large to take in the whole of the image cast on it.[1]

[1] It should be mentioned that to minimise diffraction the slits should be used fairly wide. Hence a long collimator such as described and a good

The image of microscopic objects can be thrown on the screen if these objects are well illuminated, and although dim, yet they can be viewed on the transparent screen P with ease. The images are such that they can be well photographed.

dispersion will be necessary to obtain the best definition of the sun's image.

The prism can be replaced by flat diffraction gratings with most satisfactory results. The gratings employed by the writer had about 6000 and 12,000 lines to the inch. The images were sharply defined, but, of course, weaker than when the prism was employed. For solar work this should not be an objection, since there is plenty of light to work with.

CHAPTER V

THE SOURCE OF LIGHT TO USE WITH THE APPARATUS

We must next consider what should be the source of light to be used with the two forms of colour patch apparatus just described. It is evident that the source must be an intense one when the spectrum is even but 3 in. long, for it has to be remembered that a narrow slice of light has to be taken from the spectrum, and that this has to be spread out into a square patch of light of some 2 in. side. Suppose the width of the slice of light be $\frac{1}{20}$ of an inch, and its length 1 in. Then the area of the beam at the issuing slit is ·05 sq. in. The patch of light of 2 in. side is therefore $\frac{\cdot 05}{4} = \cdot 0125$ less bright than the slice of spectrum colour. The brightness of the spectrum of any source, such as a candle or incandescent light, is small, and if this were used the brightness of the patch of light would be so enfeebled that the colours might be bleached to some large extent in consequence of its enfeeblement (*vide* pp. 97 *et seq.*).

Further, there is but very small intensity in the blue end of the spectrum, which, even with a strong and whiter source of light, is only just sufficient to be useful for measuring purposes. These two facts prevent either of these sources from being as a rule employed; hence we have to cast about to see what light will be most

suitable—that is, be readily available, and remain of the same quality.

One naturally turns to the sun as a source; but here again we are met by difficulties, even supposing that sunlight was always available.

Sunlight.

It will be advisable to enter into some detail as to the objections to its employment, which incidentally will also apply to sky light. The light from the sun at midday, even if vertical over our heads, has to traverse the thickness of the atmosphere before it reaches our eyes. Except in the tropics, the sun is never vertically over us, but is at midday at some less altitude, and consequently has to traverse a greater thickness than one atmosphere. It may be objected that the atmosphere varies in density, as the greater the distance from the earth's surface the less is the density. As a matter of fact, this does not affect the question, except as regards refraction, and the whole of the atmosphere may be considered as homogeneous throughout in calculating atmospheric thickness. The height of this homogeneous atmosphere is determined by the height of the mercury barometer. The specific gravity of mercury is 13·6 times that of water, and water 815 times that of air. As about 30 in. of mercury balances the pressure of the air, it has been calculated that the atmosphere extends upwards about 50 miles. As the sun sinks towards the horizon, the thickness of atmosphere through which the light passes gets greater and greater, until, according to Bougier and Forbes, at the horizon it has to pass through about $35\frac{1}{2}$ atmospheres. (This limit is due to refraction. For all ordinary altitudes of the sun the thickness is given by sec θ, where θ is the altitude.) If the air were

totally transparent, the amount of light reaching some place on the earth's surface would be the same at whatever altitude above the horizon the sun might happen to be; but there is some small loss of light due to the absorption by the atmosphere, which may be supposed to be feebly coloured, and a much larger one due to the fact that there are innumerable very fine particles suspended in it, which produce an effect which utterly differs from those produced by the colour of a transparent body.

Fine Particles in the Atmosphere.

Lord Rayleigh, in a mathematical investigation into the effect produced by very fine particles in the path of a ray of white light, found that they scattered the light in all directions, and that the amount of scattering depended on the 4th power of the wave-length.

Thus with waves of light with lengths varying as 2 to 1, sixteen times more of the first than of the second would pass through an atmosphere charged with small particles. The greater the number of particles—that is, the thicker the atmosphere through which the light has to pass—the greater will be the loss of intensity of the rays of short wave-length. In other words, as the sun sinks to the horizon the light which reaches the eye becomes yellower, until at the horizon it becomes red.

[A pretty experiment can be performed to illustrate the change in colour which takes place by the passage of a beam from the crater of the arc light, when a number of fine particles through which it passes is increased. Using an optical lantern illuminated by an arc light, we can throw an image of a small circular aperture cut out in an opaque plate on the screen, which we may suppose to be an image of the sun. If in the path of the beam

we place a flat cell containing a solution of hyposulphite of soda (1 of salt to 10 of water), the disc still remains uncoloured, but if we add a small portion of dilute hydrochloric acid (1 part of acid and 10 of water) to the contents of the cell, the hyposulphite immediately begins to decompose, and very fine particles of sulphur are produced in suspension. The image on the screen begins to get yellow, and gradually becomes orange, and finally red, the various stages through which the image passes indicating the diminishing intensity of the colours produced by the shorter wave-lengths. This can also be exemplified very beautifully by throwing on a screen a longish spectrum of the light of the crater of the arc by means of the lens L_1 (Fig. 15), and placing the cell with fresh hyposulphite solution in front of the slit. The colour of the light, which is analysed, can be shown by the patch of reflected light. When the acid solution is added with much stirring, the first effect on the spectrum will be a dimming of the violet, then a further dimming of the same colour, and also of the blue. After a while the green will, with the colours just named, begin to fade. The yellow will next follow, and finally only the red will be light visible. An ocular demonstration of the loss of colour is very convincing. The colour of the fine particles does not matter. The particles are so fine that the light is not transmitted through them (to any appreciable extent at all events), and whether it be small particles of sulphur or of any other material, such as smoke, the phenomena detailed above will be observed when a beam of light is passed through them.]

The following table, which has been published,[1] gives the calculated values of sunlight colours after passage through different atmospheres.

[1] "Colour Measurement and Mixture," *S.P.C.K.*, and Papers Nos. 8, 9.

TABLE I.

Fraunhofer Line.	Wave-Length. λ.	Light after passing through Atmospheres of the following Thicknesses.									
		0.	1.	2.	3.	4.	5.	6.	7.	8.	32.
A	7594	1·000	·955	·908	·857	·815	·775	·736	·707	·665	·107
B	6867	1·000	·926	·858	·795	·735	·684	·632	·583	·542	·086
C	6562	1·000	·912	·832	·759	·693	·632	·576	·526	·480	·019
D	5892	1·000	·868	·754	·655	·569	·494	·428	·372	·323	·001
E	5269	1·000	·803	·644	·518	·427	·334	·268	·216	·173	...
F	4861	1·000	·738	·544	·402	·296	·219	·161	·119	·088	...
G	4307	1·000	·609	·367	·220	·137	·084	·051	·031	·019	...
H	3968	1·000	·506	·254	·128	·071	·033	·016	·008	·004	...

This table was derived from a long investigation of the value of the coefficient of scattering due to the number of particles present, according to Lord Rayleigh's formula, which may be taken as

$$I' = I\epsilon^{-\lambda^4 n}$$

where I is the original light before transmission, and I′ that after passage through the particles, λ is the wave-length, and n is a constant. The author found that the smallest value of n was ·0013 when λ^{-4} was, for convenience' sake, multiplied by 10^{17}, and that the mean value was ·0017. The table is calculated after using the mean value.

It may be useful to give the approximate brightness of total sunlight when the sun is at various altitudes :—

With	0	atmosphere,	1·000
At 90°	1	,,	·840
,, 30°	2	atmospheres,	·705
,, 19° 30′	3	,,	·594
,, 14° 30′	4	,,	·496
,, 11° 30′	5	,,	·417
,, 9° 30′	6	,,	·303
,, 8° 20′	7	,,	·256
,, 7° 30′	8	,,	·215
,, 0°	32	,,	·002

The numbers in the third column are derived from luminosity curve of the sun's brightness, taken by the method described in Chapter VIII.

The calculated difference in brightness of the sun is very marked as it approaches the horizon, which agrees, it is almost needless to say, with observation.

Sunlight at Heights above the Sea.

So far we have only dealt with sunlight at sea level; but before going further it is well that we should note that as we move our place of observation higher above the sea, the factor n in Lord Rayleigh's formula gets smaller and smaller as we ascend. During several years the writer made observations[1] of total sunlight at heights up to 14,000 feet, with the sun at various altitudes. His plan was to expose to the perpendicular rays of the sun a standard platinotype photographic paper for fixed times. Calling to his aid a fact which he had found, that for visual rays the relative brightness of sunlight could (except when the sun was very near the horizon) be measured by taking a single ray in the yellow (λ 5570) of its spectrum, and measuring the intensity of that ray only, he applied the same plan to the photographic paper he employed. The platinum paper would be regarded as a light-registering surface for all the rays to which it was sensitive, differing, of course, in amount from the rays to which the eye was sensitive. He made experiments to find which single ray in the blue of the spectrum would be equivalent to the total light acting on the platinum paper. This was found to be a wave-length (λ 4240). The darkening of the developed platinum paper, after ex-

[1] See Paper No. 9.

posure for fixed times at different stations, was carefully measured. The observations made at the widely varying altitudes were finally calculated as if the variation was due to the variation of the wave-length (λ 5570). This enabled the factor for the scattering of light to be found, which would be applicable to every ray of the spectrum. The observations made during the three years show that the factor n in Lord Rayleigh's formula varies as the height of the barometer at the place of observation. Thus if the n is ·0013 at 30 in. of barometric pressure, it is only ·00065 at 15 in., and at 10 in. would only be ·00043. Enough regarding sunlight has now been said to show that it is untrustworthy as a standard; that even in a cloudless sky its quality (*i.e.* the relative brightnesses of the different rays) varies, and that the variations differ according to the altitude at which observations are made.

Sky Light.

The next natural source of light is the sky, and here we are met with precisely the same kind of difficulties which are found with sunlight. The light which is scattered away from a sunbeam by the fine particles falls on other neighbouring particles and illuminates them, and part come to the eye. Lord Rayleigh made an investigation into the light from the sky and found that the light coming from the fine particles as "sky" light was more or less polarised, the polarisation taking place most strongly in a direction at right angles to the direction of the beam of sunlight falling on the eye, and that its blueness was due to the greater scattering of the rays at the more refrangible end of the spectrum. The light coming from the sky

and the sunlight reaching our eyes, if mixed together, might thus give us the original colour of the sunlight as it issues from the sun itself. It is perhaps impracticable to make such a mixture owing to the fact that a proportion of the scattered light must go away into space, but it indicates that sunlight at noon on a summer's day must be slightly less blue than the light which enters the atmosphere. The polarisation of scattered light can be shown in a simple manner, and the experiment is one which imprints the fact upon the memory.

Polarisation produced in Scattered Light.

[If we take a cell some 3 or 4 in. long and pass a thin pencil of light through its length, such, for instance, as is given by sending a beam of light through a small circular aperture placed in an optical lantern, there will be no appearance of the light in the interior of the cell. If, however, we fill the cell with water in which common mastic varnish has been precipitated, the turbid liquid at once shows the track of the light and becomes illuminated. The pencil of light will appear whitish at the end of the cell near the aperture, and will be seen as yellower when it approaches the other end. (A screen placed near this end of the cell will show the colour of the pencil after it emerges.) If between the lantern and the cell is placed a Nicol's prism which is rotated in one direction, the track of the pencil, when observed at right angles to the direction of the pencil, will gradually fade away, and will finally become invisible, as will the illumination of the water; whilst if it be further rotated 90°, the track and the water in the cell become visible once

more. In this experiment the small particles act like the small particles in the air.[1]

This investigation of Lord Rayleigh's, which General Festing and the writer, it is believed, were the first to confirm experimentally, enabled an experiment to be made first of all by Sir George Stokes, by which the debated point as to whether a candle or gas flame was luminous owing to solid particles being rendered incandescent could be settled. If the pencil of light (sunlight by preference) be directed through a candle or gas flame instead of through the turbid medium, a track of the pencil can be seen when examined at right angles to the pencil. When the Nicol's prism is inserted and turned in one direction, the track will be invisible; if turned in the other direction it will reappear.

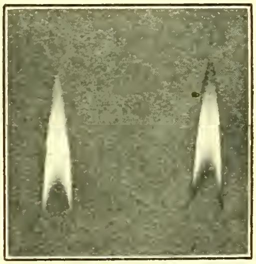


FIG. 20.

Fig. 20 gives copies of photographs made of the phenomena.

Such evidence tends to prove that the particles are solid, though extremely fine. In other words, there does not seem to be much difference in the source of light from an incandescent electric light and that of a candle flame: both appear to be due to incandescent solid carbon. It may, however, be remarked that the illumination given by a flat gas flame, when it is turned flat side towards an object, will not be quite the same as that given when the flame is turned end on. The reason for this is apparent.]

[1] It may be stated that the suspended particles become finer if the water be allowed to rest for a month or two.

Nature of Atmospheric Fine Particles.

It has been a somewhat disputed point as to what the fine particles in our atmosphere consist. Lord Rayleigh, in a more recent paper than that referred to, has calculated that the sizes of the molecules of the gases which make up the atmosphere are sufficiently large to cause the sky to be bluish, but they can hardly account for the deep blue which is often seen overhead. It seems more probable that the main sources from which the blueness is derived are dust and the particles of water which are in a semi-vaporised condition. These would amply account for it. We have often good circumstantial evidence before us that such water particles will produce the effect required. The sky is not only above us, but it is everywhere above the ground. We often look at distant hills and find that they have a blue haze in front of them which profoundly alters the local colouring. Or again, if we look at a very distant snow mountain we find that not seldom the whiteness of its snow is tinged with a yellow which can only be due to the passage of the white light reflected from it through fine particles which intervene between the eye and the mountain. There are dry days when this is seen to the greatest advantage. When the atmosphere is moist, it is a matter of common observation that distant hills show their local colour, and stand out so that one can "almost touch them." On these same kind of days the snow of the far-distant snow mountain will appear white and not yellow. On such a day we have the fine particles coalescing from bigger drops or particles which are too coarse to scatter the light, and hence no large amount of blue is produced by scattering. From observations and calculations made, it almost appears that

aqueous particles are of two sizes, one of which is quite small enough to be compared with a wave-length of light, which is a measure of the suitability of the particles to scatter light, and the other considerably larger, and does not scatter selectively. Be this as it may, evidence goes far to prove that aqueous particles can give rise to the phenomena of "scattering."

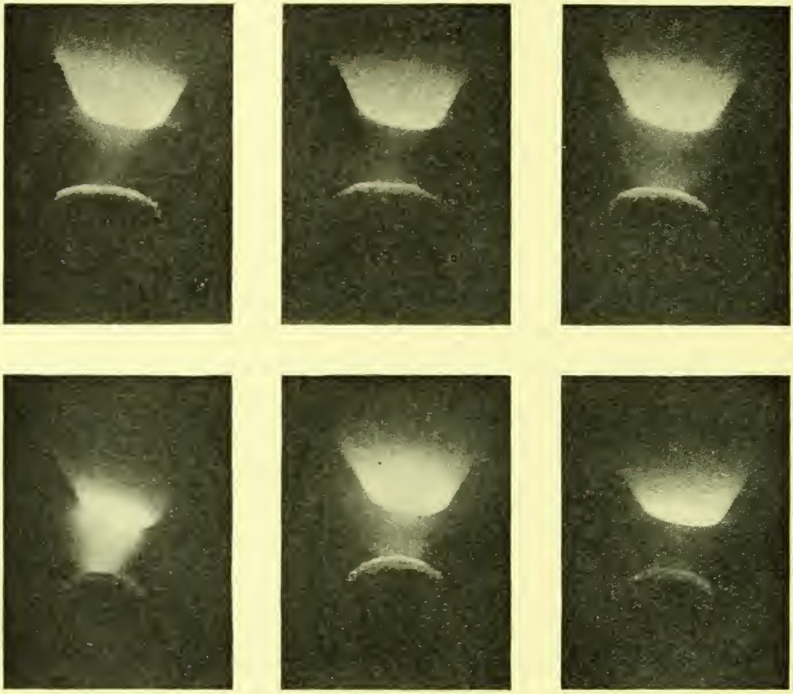
Even were the sky free from cloud, it is unsuitable for the purpose of a source of light, for the greatest intensity available is only a disc, which has the same angular dimensions as the collimating lens when viewed from the slit.

Light from the Crater of the Positive Pole.

As already indicated, the best and most constant source of light to obtain a measurable patch is the crater of the positive pole of the electric arc light, and this involves the use of a direct current of electricity. The crater is a small circular to oval space on the positive carbon which is at an intense white heat, and if a "cored" carbon is used for the positive pole it appears as an almost uniform surface, probably in a semi-liquid state. The violet rays of the arc are present, but if the negative pole be the top pole and be placed a little in front of the positive pole the spectrum of these rays is reduced in intensity and practically does not interfere with the far stronger spectrum of the white-hot crater. In Fig. 11 a lens is shown in front of the collimator slit. This is so placed that an enlarged image of the crater is thrown on to the slit, filling it completely, and if the diameter of the lens is sufficient the collimating lens will also be entirely filled. Fig. 21 shows six different images of the poles of the arc light taken in—(1) red;

(2) orange; (3) yellow; (4) violet; (5) blue; and (6) green monochromatic light (see p. 50). In the red image the photograph shows the positive pole luminous —that is, red hot—some distance from the crater. In the orange image the heating apparently does not

Red. Orange. Yellow.



Violet. Blue. Green.

Fig. 21.

extend so far. The yellow, blue, and green images show less of the positive pole, *i.e.* shorter lengths of the carbon are luminous. The violet image shows only the crater as heated to "violet" heat. Here we have evidence that the temperature of the carbon at different distances from the crater varies. Some distance below the points we have red heat, then

it has yellow heat; finally an intense white heat is generated in the crater. This white heat is practically constant and of uniform temperature. In fact, the photograph taken with the red rays shows where the carbon becomes red hot, and with the green rays where it has a temperature intermediate between that of the crater and red heat. It may be remarked that the size of the crater varies with the size of the carbons and with the current employed. In our own sloping lamp the carbons are 13 mm. in diameter, and the voltage 115 volts, and about 11 amperes of current are used. The diameters of the oval crater are about 7·5 and 5 mm., which are enlarged by the lens from two to three times.

Arc Lamps.

As regards the light, it is advisable, for the sake of comfort, to use an automatic lamp with the positive pole remaining always at the same height. The sloping lamp we have used is a Brocky-Pell or else an Oliver lamp (by preference the last). Where there is an assistant to attend to the lamp, one of the comparatively cheap "scissors" motion lamps can be used, and is satisfactory, the image of the crater being kept on the slit by the movement of the "scissors." The light may be placed in a darkened room in a lantern which practically cuts off all light except that coming through the lens used to give the image of the crater on the slit. It is convenient to have the lantern *outside* the darkened room and to admit the light through an aperture made in the wall. This leaves the darkness in the room practically complete, and for some purposes this is necessary.

The quality of the "crater" light with these two lamps and with the same carbons never seems to vary—

that is, the relative brightness of the different rays do not alter, though the quantity of light forming the spectrum may diminish to some extent if the slit has not been kept entirely covered by the crater's image. For this reason the device of using the reflected beam as a comparison light is of the greatest use. More recently the writer has been using a lamp with the carbon for the positive pole in a horizontal position, the negative carbon is below and nearly at right angles to the other. The carbons are larger and take about 22 amperes at 100 volts. When this light is employed, its "quality" is a little different to that just described, the spectrum increasing in brightness in the yellow, green, blue, and violet. This may be due to the greater amount of light from the very hotest parts of the crater falling on the slit, or to some necessary alterations that were made in the optical arrangement outside the slit. When this lamp is used, the relative luminosities of the different rays remain the same.

Nernst Lamp.

Quite recently the Nernst lamp has been used in the writer's laboratory as a source of illumination. The means by which it becomes workable was devised by Professor W. Watson. The Nernst lamp is on the same principle as a glow-lamp, but in some forms the filament [1] is single and of such a length that the whole of it can be placed in the collimator tube. Professor Watson employed the white-hot filament in *place of the slit* and at the focus of the collimating lens. The diameter of the filament is so thin that it answers for a slit of fairly open aperture. The white-hot filament is enclosed

[1] It is not a carbon filament, but is composed of a compound of rare earths such as cerium.

in a metallic box, which is practically light proof and which can be removed from the collimator when required. The spectrum of this light when the current passing is 1 ampere and the voltage 100 is bright. By using a "combining lens" for the spectrum of shorter focus a smaller patch is formed on the screen sufficiently bright to be readily measured. Such a light has the advantage of being perfectly steady. It is too early to state that the quality of the light remains the same, but measures seem to point to the fact that the light emitted from different filaments is always of the same quality as long as the amperes and voltage are maintained constant.

CHAPTER VI

THE APPARATUS TO ALTER THE INTENSITY OF THE LIGHT

It is necessary to have some means by which the intensity of the light coming through the spectrum slits, or that of the reflected beam, can be altered at pleasure whilst observations are being made, and the writer has found that the plan of rotating sectors in the beam, with a good velocity, will give results which compare favourably with that of moving a comparison light.

Sector Apparatus.

The figure shows a sector which can be opened and closed during rotation in a very simple way. One sector (the sector S) is attached to an axle, M, and the other sector (S′) is attached to a hollow axle, N, fitting accurately the axle M; a sleeve, A, fits over N. In the axle M a spiral channel is cut, in which a pin with a rounded head, fixed to the sleeve A, runs. A lever, fixed to a support (not seen in figure), carries a fitting which clasps each side of a projecting boss, B. When the lever is pushed to the right or left, the boss moves with it, and at the same time the pin attached to it travels in the spiral channel on the axis and compels the sector S′ to open or close the apertures between the segments. A pulley, C, is attached to the axle, and a leather or thread band passes over it and the pulley D, which is attached to

a motor, E. When the sectors are rotated by means of the motor, the apertures can be opened or closed by the lever H at will. The rims of the sectors are graduated in degrees of arc.

There have been various attempts made at some time or another to prove that the sectors do not give a diminution in light proportional to the

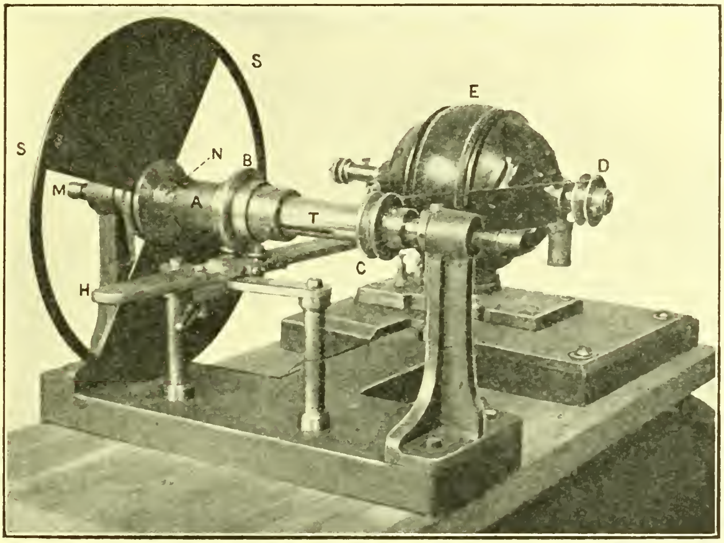


FIG. 22.

degrees of aperture. It was not till after exhaustive trials that the writer adopted the sector method for the purpose of assisting in colour measurement. Lights of various colours were reduced by the sectors against a light which could be moved away from a screen to any required distance, and in no single case did the sector give any other value than the correct one. It should be stated that the sectors are only applicable for accurate measurement when the angles of aperture lie between 180° and 10°. There is always a small

amount of backlash with the sectors themselves, which, when the angles are smaller than about 10°, might cause an appreciable error in the measures. The error is so small in good instruments, that when bigger angles are used it becomes trifling in comparison with the errors which may be expected in all such visual observations. (If anyone wishes to make sectors of this kind, a less complicated plan is to use an American drill for the axle.)

Annulus Apparatus.

Another plan for reducing light is by what the writer has called an annulus, which is a gelatine wedge in annular form. The late Mr. Leon Warnerke brought out a "sensitometer" (an instrument for measuring the sensitiveness to light of a photographic plate), in which the apparatus for reducing the intensity of light admitted to a sensitive surface consisted of an annulus of gelatine of gradually increasing thickness, coloured either by a dye or by incorporating with the gelatine a powder of any colour which might be desired. Mr. Warnerke made a mould as follows: In a perfectly flat disc of steel a circular groove of uniformly increasing depth is cut out by a proper machine till the ends of the groove form a circle. The depth of the groove, when tested, was found to increase proportionally to the arc of the circle, and replicas of the disc, with its groove, are made in non-oxidisable metal. For our purpose the finest ivory black is mixed with a semi-liquid gelatine, and when thoroughly incorporated the viscous material is poured into the groove, the top surface of the disc being accurately levelled. A sheet of worked glass is then laid on the surface

of the disc, and any excess of gelatine is squeezed out, except a very fine film, which appears colourless. When the gelatine has properly "set," the glass plate is removed with the relief of the groove attached to it. The gelatine annulus is allowed to dry, and is then ready for use. The writer had a large batch of these gelatine annuluses prepared, some giving small differences in the light, which passed through the thin end and the thicker end of the relief. (It may be said that the relief is so small that no prismatic effect can be traced.) Others gave a medium range of increasing density, and yet others a very steep gradation, quite useful for extinction purposes. The annulus was tested as to the transmission of coloured light, and it was found that from the extreme red to about the G line in the violet of the spectrum, every ray was equally obstructed. The graduation of the annulus should give intensities which varied as the log of the arc. The various annuluses were tested, and about one out of every three gave a graduation which was practically perfect.

The following is the method of mounting the annulus. A hole is pierced exactly at the centre of the circular disc (as shown in F). The disc of glass, A, is also pierced with a hole in its centre, the hole being just of the size sufficient to allow a pin, with a screw thread springing from a brass plate attached to the wooden slide, to penetrate. The disc of glass, F, is pressed on to the pin, and the two glass plates are clamped together by a mill-headed nut, D, a washer of paper, E, being placed between the two. The disc, A, is cemented into a circular ring, B, graduated into degrees. On A is ruled a line joining the centre and the zero of graduation. The junction

of the most opaque and transparent parts of the annulus

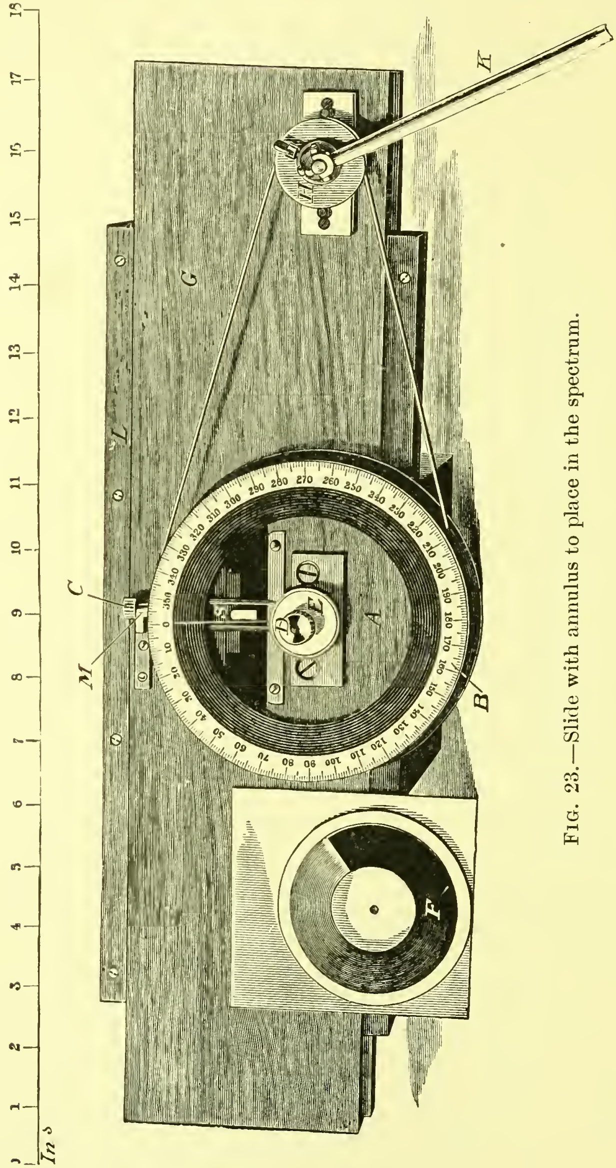


FIG. 23.—Slide with annulus to place in the spectrum.

is made to coincide with the zero point and the line ruled on A. In the wooden slide is placed a metal

slit, S, with movable jaws opening centrally. When vertical, the line ruled on A passes through the centre of S. In the wooden slide G a transparent scale similar to that shown in Fig. 12 is inserted. The brass circle, C, can be caused to move round its centre by a thread passing over it and a small-toothed pulley, to which is attached a long arm, B, that causes the pulley to rotate when it is turned.

[The annulus in ordinary use has regular gradation for each degree, the coefficient of obstruction (it is not exactly absorption) being 0·0086 for each degree.]

To use the annulus in the spectrum, the slide bearing it is placed in the place of the slide D of the colour patch apparatus. When using it in the reflected beam, the slit S is placed in the position where the rays from the reflected beam cross, and which is really the image of the collimator slit. By the long arm mentioned, the annulus can be rotated and the intensity increased or diminished. A comparison of measures between the sector and the annulus shows the results to be identical.

CHAPTER VII

INTENSITY OF SPECTRUM COLOURS

The first and simplest measure of colour to make is that of the intensity of the spectrum colours which are transmitted through, or reflected from, coloured bodies. The various methods which we have adopted will be described in this chapter. The intensity of a spectrum colour transmitted (or reflected) we will define by the percentage brightness that it bears to the same colour unmodified by transmission or reflection. Thus, supposing it is found that after transmission through a green glass, the sodium light at D is (after making certain corrections), only half as bright as that which falls on the glass, then the intensity of this colour is ·5, or 50 per cent. Evidently it is convenient to have what we will call the naked light compared directly with that which passes through, or is reflected from, the medium. The first method that will be described is the latest in point of date, and is perhaps the most satisfactory.

Modification in the Apparatus to form Two Beams of the Same Colour.

The single colour patch apparatus may be used for the purpose. A single slit is used in the slide at D, Fig. 13. Between it and the colour patch is placed on a suitable block a bundle (M_1) of plane and colourless glass plates (Fig. 11) about 5 in. long by 3 in. deep. The 5-in. length makes an angle of about 45°, with the

ray issuing from the slit S, and the 3-in. side is vertical (Fig. 24). The bundle is so placed that the whole of the spectrum has to pass through it after it has passed through the lens L, which forms the patch on the screen. The glasses and the bundle are separated one from another by the thickness of a strip of paper at their edges. Any ray falling on the bundle is divided into two parts; one is reflected about 90° from its original path and the other passes through it as shown in the same diagram. The silvered mirror M_2 reflects the light from the glass bundle on to the screen, and forms a patch which can be superimposed on the patch formed by the direct beam.

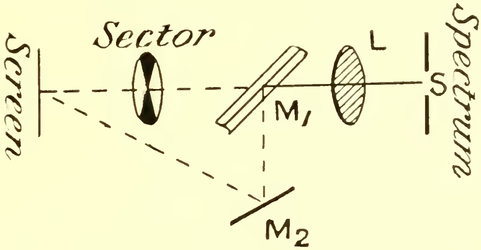


Fig. 24.

A sector can be placed in the path of either beam, so as to diminish their light at will.

The amount of light which should be reflected from the bundle, it is often supposed, can be calculated from the number of individual plates in it, when the angle of incidence at which the light falls is known.

The calculation is, however, not always to be relied upon, owing to defects in the glass, want of perfect parallelism of the surfaces, and the variable absorption. It is easier to determine experimentally the total amount that is reflected. The following table gives the results of some measures made with the bundle we employed when the incident beam made an angle of 45° with the surface:—

1 glass reflects 12·5 per cent.	4 glasses reflect 32 per cent.
2 glasses reflect 22 ,,	5 ,, ,, 34 ,,
3 ,, ,, 28 ,,	6 ,, ,, 35 ,,

It will be seen that after six glasses are in position, there can be no very little marked alteration in the percentage reflected. Of course, the amount reflected has to be deducted from the total amount coming directly on to the screen, besides that which is lost from absorption by the glasses, which, it may be stated, is by no means small.

Measurement of Absorption of Transparent Media and of Pigments.

The transparent medium the absorption of which has to be measured is placed in the direct beam of light. Two shadows, side by side and touching one another, are cast on the screen by placing a rod in the path of the two sets of rays. One is illuminated by the direct ray which comes through the medium whose absorption is to be measured, and the other by the reflected beam which has not passed through it. The illumination of the two shadows are equalised by placing the sectors in the path of the reflected beam. If necessary, another set of sectors, set at known angles, can be placed in the other beam. The writer usually commences with a ray in the red. The percentage of loss of the direct ray owing to absorption is ascertained by substituting for the transparent medium a colourless glass and again equalising the shadow illumination.

Let us take as an example a green glass, the absorption of the D (sodium) light by it being required. With this glass in position, the rotating sectors in the reflected beam showed 15° of aperture as necessary to equalise the shadow illumination, but with the colourless glass it required 36°, the sectors being in the direct

beam in both cases. The percentage intensity of the ray passing through the medium was therefore 41·7 per cent. of the original beam.

The simplest way of calculating the result when the sectors have to be changed from one beam to the other is to multiply the readings by one another and by 100, and to divide by $(180°)^2$. In the above example, if the sectors had been placed in the direct beam for the second reading, we should have—

$$\frac{15 \times 36 \times 100}{180 \times 180} = \frac{100}{60} = 1·67$$

—that is, the percentage of light transmitted would be 1·67. Taking another case, the reading of the sector in the direct beam with the colourless glass interposed was as before, viz. 36°, but in order to equalise the shadows when the coloured glass was in position a second sector had to be inserted in the path of the direct beam, which was fixed at 60°, and the reading of the moving sector in the *reflected* beam was 62. Had the direct beam been left without a sector, it is evident that the reading would have been 186°, since only one-third of the direct beam was allowed to pass. As before, the actual readings are multiplied together, as also by $100 \times \frac{180}{60}$ and divided by 180^2, that is, $\dfrac{62 \times 36 \times \frac{180}{60} \times 100}{180 \times 180} = 20·7\ \%$.

These calculations are of course done after the observation. It may be said that at least three readings should be taken for each scale number, and the mean used for the calculations.

The following is a complete table of the observations and calculations made for ascertaining the intensity of light passing through an inch of a saturated solution of

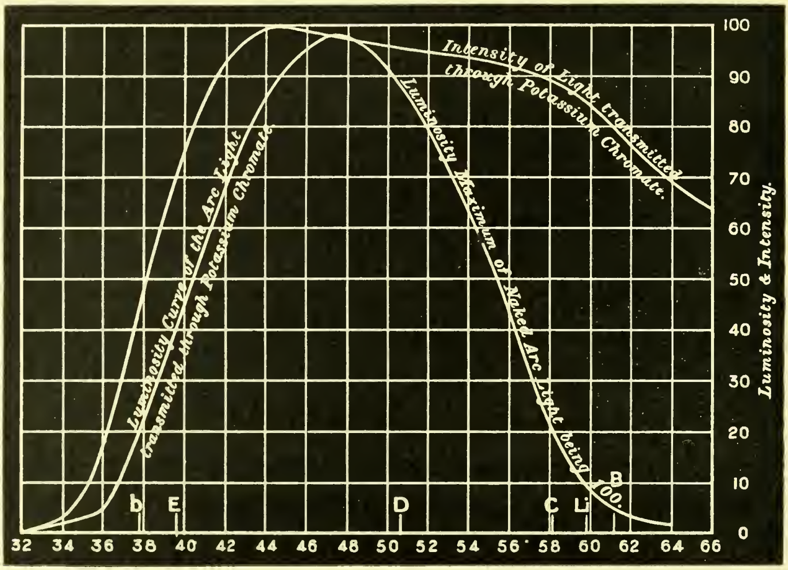


FIG. 25.

TABLE II.—*Intensity of Light transmitted through Potassium Chromate; also the Luminosity.*

SSN.	Intensity of Transmitted Light (Naked Light being 100).	(Horizontal Carbon.) Luminosity.	Luminosity of Transmitted Light.
64	68	1	·68
62	75	2	1·5
60	83	8·7	7·2
58	88·5	21·3	18·8
56	91·5	48·3	44·2
54	92·5	70	64·7
52	94	84·7	79·6
50	95·5	96·2	91·9
48	97	100	97
46	99	95	94
44	100	85·3	85·3
42	93·5	72	67·3
40	77	56·1	43·2
38	50	41	20·5
36	16·5	27·5	4·5
34	2	15·8	3·2

chromate of potash. The luminosity is shown, as it will be required to be known later.

When the intensity of the colours reflected from pigments is required, very much the same procedure is followed. The only difference is that one half of a square surface of, say, $1\frac{1}{2}$-in. side is covered with the pigment and the other half with white, the shadow illuminated by the direct beam falls on the pigment,

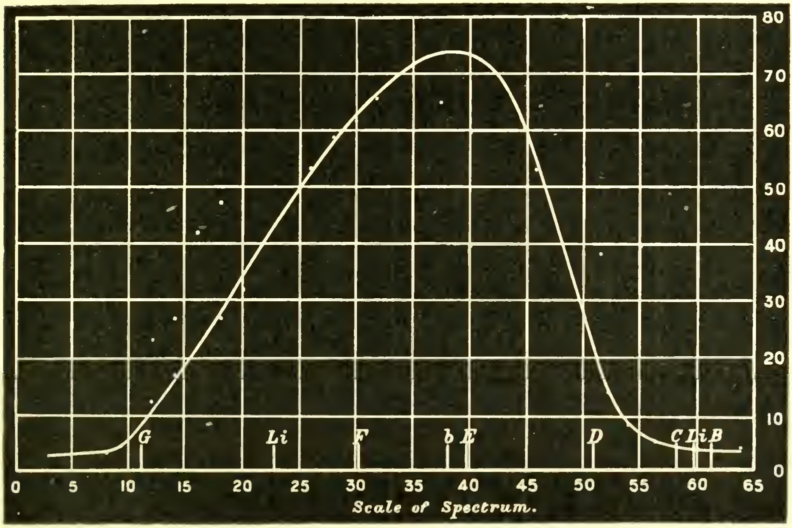


FIG. 26.

and the white is illuminated by the reflected beam. The equalisation of the illumination of the shadows is effected in precisely the same way as that described when the colour intensities of the transparent medium were being measured. The percentage reflection is arrived at by substituting a square of white paper for that made up of pigmented paper and white. The rod, of course, is employed to cast the two shadows in each case. The diagram (Fig. 26) and the following table show the light reflected from a specimen of emerald green.

TABLE III.—*Emerald Green Pigment.*

Spectrum. Scale No.	Readings.			Reading. Mean.	Corrected Ordinate from Diagram.
	1	2	3		
64	3·5	3·5	3·5	3·5	3·5
62	3·5	4	3·5	3·5	3 5
60	4	3·5	3·5	3·5	3·5
58	4	4·5	4	4	4
56	5	5	5	5	5
54	7·5	8	8·5	8	8
52	14·5	13·5	14	14	14
50	27	28	29	28	27·5
48	42	41·5	42	42	41·5
46	53	53	55	54	55
44	63	63·5	62·5	63	63
42	71	71	71	71	71
40	74	74	74	74	74
38	74	75	74·5	74·5	74·5
36	73	73	73	73	73
34	70	70	69·5	70	70
32	65	64·5	66	65	66
30	61	61·5	61	61	62
28	58	57	59	58	57
26	52	54	53	53	52
24	46	46	46	46	46
22	40	40	40	40	40
20	34	32	31	32	34
18	27	27	27	27	27
16	22	21·5	22·5	22	22
14	17	16·5	17·5	17	16
12	10	12	14	12	10
10	5	5	5	5	5
8	3·5	3·5	3·5	3·5	3·5
6	3·5	...	...	3·5	3·5
4	3·5	...	...	3·5	3·5

Light reflected from white = 100.

Alternative Method of Measurement.

Another plan of measurement which is suitable for the colour patch apparatus is to place a double image prism against the lens of the collimator. This will cause two similar spectra to be formed, one above the other. The separation given by the prism should be sufficient to leave a blank space some quarter of an inch wide

between the two spectra. A long slit passing through both spectra takes the place of the shorter slit usually employed in the spectrum. The double image prism is turned so that the same colour comes through the slit from the two spectra. In front of the top part of the slit a right-angled prism, A, is attached to the slide carrying the slit. This reflects the rays coming from the top spectrum along the slide, and these are again reflected by a second right-angled prism, B, on to the screen. The rays from the bottom spectrum go direct to the screen on to the same square as that on which the reflected beam falls. A rod placed in the path of the rays causes two shadows to be cast, which are illuminated as before. It is convenient to have the two right-angled prisms attached to ball and socket joints, which can be fixed by screws. The ball and socket is attached to a knitting-needle, which passes through a hole in a brass plack which is attached to the slide. This enables the patch of light to be adjusted to fall on any desired part of the screen or on one side of a cube. The illumination of the two shadows are equalised as before, and if the same colour[1] passes through the slit from each spectrum the sectors should not require to be altered when the colours from the naked spectra are used; any alteration shows that the double image prism requires adjusting. The light coming through transparent media and reflected by pigments may be measured by this apparatus, the necessary parallax being obtained by the distance of the second from the first reflecting prism.

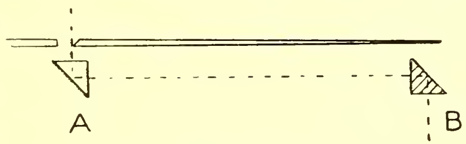


Fig. 27.

[1] The D light is the best light to use for adjusting the spectra, as a minute error can at once be detected by the colour of the two patches.

Disc Method of Measurement.

Another simple plan for the measurement of the intensity of the colours reflected from pigments is to use a revolving disc the outer ring of which is made up of adjustable black and white discs. The centre is covered with a disc of paper on which the colour to be measured has been spread. [Pigments can be readily painted on white paper of such a thickness that the white of the paper is completely hidden. A few drops of hot gelatine solution are dropped into a mortar and the pigment well mixed with it, a little hot water being added till it is sufficiently fluid to enable a hog's bristle brush to take it up. The paper is pinned on to a board and the brush worked up and down and across till it appears evenly coated. It is then allowed to dry, and a second coat given.]

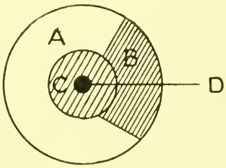


Fig. 28.

The appearance of the disc is that shown in the figure.

A is white paper which has been coated with zinc white. B is black paper which has been coated with ivory black; it should be dull and matt. C is the pigment, which is also matt. D is the screw which attaches the compound disc to the shaft of the small motor which rotates it.

The white and black discs have a cut made radially from the centre, so that they can be interlocked as shown (see Fig. 45). There is a small amount of white light reflected from the black surface, and this has to be determined. The most convenient method of making the determination is by the colour patch apparatus. A square surface of about $1\frac{1}{2}$ in. is half covered with the

black and half with the white. The black should be illuminated with the recombined spectrum white and the white surface by the white reflected beam, and a rod be used to cast two shadows. The illumination of the shadows is equalised as before, and knowing from measurement the ratio of the two white lights, the percentage of white reflected from the black pigment is calculated. A good black should not reflect more than $3\frac{1}{2}$ per cent. of light, and should be the same for every colour.

To ascertain the amount of light reflected by the pigment, the compound disc is placed in the colour patch as shown. The outer ring is given a known proportion of black to white. The disc is rotated and the slit through which colour issues is moved along the spectrum until a place is reached where the central disc and the outer ring both appear to be equally dark. The scale number of the spectrum colour is read off, and the proportion of black to white altered. The disc is again rotated, and a reading obtained as before. It must be remembered that with certain pigments, such as green, there are two places in the spectrum where the equality of illumination between the centre and the ring appears the same, and in some few cases there may be more than two places. It should be ascertained before the measures are finished that there are sufficient scale numbers noted to enable the results to be shown graphically without large gaps appearing between the ordinates. To show the intensity graphically, the abscissæ are the scale numbers and the ordinates the percentage of white which is used. This last must

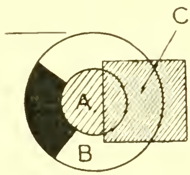


FIG. 29.

A is the pigmented disc.
B is the black and white disc.
C is the colour patch.

take into account the white light reflected from the black.

To take an example of the calculation, we will suppose that the black occupies 270° of the circle and the white 90°, and that the white light reflected is 4 per cent.

Four per cent. of 270 is 10·8, so that the total white is $90 + 10{\cdot}8$ or $100{\cdot}8°$. The percentage of the colour reflected from the central disc is therefore $\frac{100{\cdot}8}{360} \times 100$ or 28 per cent.

[It is convenient to divide the circumference of the circle into 100 parts, so that the readings are easily calculated.

In this case the readings would be 75 black and 25 white, 4 per cent. of 75 is 3, and the white used is $25 + 3 = 28$ per cent. as before.]

Measurement of Iridescent Colours.

There are instances of reflection which cannot be dealt with quite so simply. Take, for example, the colour of glass flashed with silver. By transmitted light the glass is canary coloured, but by reflected light a beautiful peacock blue. To obtain the intensity curve of the blue is somewhat difficult. The piece of yellow glass is backed with black backing in shellac, so that practically no light can be reflected from the back surface. A piece of white paper is pasted on the flashed surface of the yellow glass, and a black mask is cut which allows a rectangle of the iridescent surface of the glass to show and an equal rectangle of white. The glass is placed at such an angle that with white light the iridescence is seen. The bundle of glasses, as

before, reflects part of the ray, and the light transmitted by the bundle falls on the iridescent surface, whilst the reflected beam falls on the white surface and is used for a comparison light. By placing the eye opposite a hole cut in a card fixed in the proper position, the surface is always viewed at the angle which gives the maximum iridescence. The readings can then be made as before.

CHAPTER VIII

THE MEASUREMENT OF LUMINOSITY

In the last chapter it was shown how the intensity of the colours of the spectrum transmitted through or reflected from coloured objects could be compared with the same colours of the naked spectrum reflected from a white surface. In this chapter it is proposed to show how an estimate of the *brightness* or "luminosity" of one colour can be compared with that of another. This is a totally different problem to that of comparing the brightness of lights of the same colour. Suppose someone is given pieces of red and green pigmented papers, and is asked how the brightness or luminosity of the colours reflected from each can be compared, the usual reply would be that it is impossible to make any comparison between them. We shall see, however, that it is not only possible, but perfectly practicable, to obtain very close values of their relative luminosities. It will have to be recollected that in estimating luminosities, the nature of the light by which the colours are illuminated has to be stated, as they will vary considerably according to the whiteness of the light in which they are viewed. The "colour patch apparatus" is one means of ascertaining the luminosities of such colours as those named above when the illuminating light is sunlight or the arc electric light. It must be here stated that practice is required to make accurate luminosity measures of two such different colours.

The Comparison of Luminosity of two Pigments.

A beginner will find it easier to make a comparison of a bright colour with a neutral colour, such as white, rather than with another bright colour. When two colours are compared with a neutral colour, it is easy to calculate the relative luminosities of the bright colours. For instance, let us suppose that by some means it is ascertained that the brightness or luminosity of the light reflected from the red pigment is 25 per cent. of that reflected from the white (*a neutral colour*), whilst that from the green is 35 per cent. The ratio of the luminosities of the two colours is evidently 25 to 35, or 5 to 7.

In order to make the comparison of the red with the white, a rectangular piece of pigmented paper, say, 1 in. × $\frac{1}{2}$ in., is placed alongside white paper (the white being oxide of zinc) of the same size, and the two are surrounded by a black mask (Fig. 30).

FIG. 30.

The patch of white formed by the recombined spectrum is thrown on the coloured paper R, and that from the reflected beam on to the white rectangle W, the two white beams being separated by placing a rod in their paths.

[It is sometimes convenient, in order to do away with fringes which may appear in the combined white owing to the different rays striking the rod at slightly different angles, to arrange the recombining lens of the colour patch apparatus so that the edge of the white image of the prism falls on the junction of the red and white patches, and only to use the rod for the purpose of casting a sharp shadow from the reflected beam on the white surface.] We will here suppose that a sector with movable

angular apertures is placed in the recombined beam. When the aperture is wide, it will be seen that the red is evidently brighter than the white. The aperture is then much reduced, when it will be felt that the red is darker than the white. Evidently there must be some aperture of the sectors which will transmit the exact quantity of light which will make both red and white of the same brightness. The angles of the sectors are rapidly altered from "too light" to "too dark" and back again, and the range of angle is gradually diminished until the observer sees both to be equally bright. The angle is noted, and the observation repeated, till the readings become concordant. The mean aperture is taken as the aperture which gives equal brightness to the two rectangles. Say that the mean aperture is 48°. The red rectangle is then replaced by a second white rectangle, and the luminosities equalised, the mean aperture of the observation giving, say, 12°. The red is therefore a quarter (or 25 per cent.) of the brightness of the white. The green pigmented paper is treated in a similar manner, and the reading is, say, 34°. This makes the green $\frac{12}{34}$, or 35·3 of the white. The ratio of the luminosity of red to green is therefore 25 to 35·3, or about 5 to 7.

In making these measures, as already said, at least three readings should be taken, and in difficult matches even more should be made. However, if the *mind has been fixed* on the necessity of noting the "too light" and "too dark" oscillations, the mean of three readings should be sufficient in most cases. When the rectangles are of the size given above, all observations should be made with the eyes at a fixed distance of about 5 feet from the patch, so that the images may all be received on the yellow spot.

Luminosity of Pigments in Artificial Light.

If the luminosity of the pigments in artificial light is required, the following plan may be adopted.

L is the light, M a silvered mirror, the pigment is illuminated by the reflected beam, and the white by

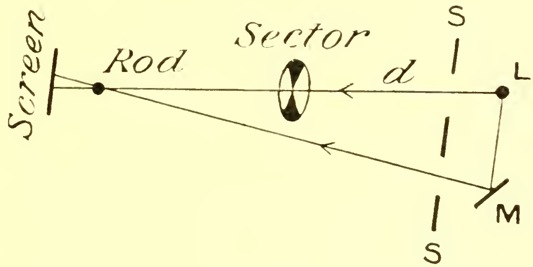


FIG. 31.

the directed beam *d*. A screen SS, with two apertures cut for the rays to pass through, is placed in the path of the two beams, and the luminosity determined as before. The light must be enclosed and observations made in a darkened room.

It cannot be too strongly impressed upon the reader that it is absolutely fatal to good results if stray light is allowed to fall on the white and the pigment, as there is selective reflection from the latter, which is by no means the same as that from the white surface.

Comparative Luminosities of Spectrum Colours as seen on the Yellow Spot.

An exact determination of the comparative luminosities of the different rays of the spectrum itself is all-important.

It should be carried out in precisely the same manner as that just described, but with the colour patch appa-

ratus. Instead of a pigmented paper being illuminated, the whole square is white. On half of the square the patch formed by the rays coming through a slit, which can be moved along the spectrum, and on the other half the reflected beam, falls.[1] A rod in the path of the converging beams prevents the overlapping of the colour and the white, and the two can be caused to touch by adjusting it. The rotating sectors have usually to be in the path of the white beam, and the oscillations of aperture will thus alter the luminosity of the white.

The slit which passes along the spectrum, of course, remains unaltered in width during the whole of the measures, so that the luminosities of the different rays are strictly comparable one with the other.

When the blue end of the spectrum is approached, it will be found that the readings of the sector apertures become very small, and, owing to a small amount of backlash, which almost of necessity exists in the sector movements (see p. 69), they may become unreliable. It is usual to substitute for the silvered mirror, which reflects the white beam, a piece of flat unsilvered glass. The ratio of the reflections of the two mirrors are very readily determined, and the readings of the unsilvered mirror can be converted into readings of the silvered mirror when once this has been found. Sometimes it has been found useful to place in the white beam a piece of blue glass, which practically absorbs all the rays except the blue and violet. When the absorption by such a glass has been found, the readings, as in the case of the plane mirror, can be converted into readings with

[1] Care should be taken that the centre of the colour patch should fall on the centre of one half square, and the centre of the white patch on the centre of the other.

the silvered mirror. (For rather smaller diminutions of luminosity, a piece of wire gauze, placed in the path of the white beam, is effective, the diminution being, as a rule, rather more than half.) Some observers find it an advantage to have the white comparison light thus converted into a blue one, as the colours in the blue and violet approach that transmitted by the blue glass. It is again necessary to repeat the warning that the eyes of the observer must always be at the same distance from the screen, and that he should be "dark adapted" (*i.e.* his eyes should be withdrawn from daylight for ten minutes before measures are read), when observations are made, in order to obtain reliable comparative readings.

Luminosity of Colours outside Yellow Spot.

For theoretical purposes, it is also advisable to determine the luminosity of the spectrum when not received on the yellow spot. To make such observations we can adopt a plan which, though it appears difficult at first, is yet easy to carry out after a little practice. In order that the image of the patches may fall outside the yellow spot, it should be received on the retina at least 5° from the centre of the eye. If a spot is marked in a horizontal direction 5 in. away from the outside of the rectangles, and the observer's eyes are 5 ft. away from the patch, and that spot is looked at, the image of the rectangles will be received outside the extreme edge of the yellow spot. The outside spot should be illuminated by Balmain's paint. One eye must be closed, and the axis of the other eye be directed to that spot. The rectangles of white and colour will be fairly defined and the luminosities can be compared. It may appear strange

that the luminosities of the two patches can be compared under such circumstances, but as a matter of fact they can be compared with even greater facility than when observed with the centre of the eye. When a comparison is being made, the colour often appears, not actually to vanish, but to become less powerful (due no doubt to causes which will be treated of in colour fields), and to allow matching in luminosity with comparative ease. The luminosities found appear not to depend on the azimuth, but to be the same all round the axis when the spot is moved in a circle round the centre of the rectangles.

If two square patches of equal size, say of $1\frac{1}{2}$ in. side, are placed 6 in. apart, and illuminated with white light of the same intensity, and the centre of the eye be fixed on one of them, the image of the other will fall outside the yellow spot. By diminishing the luminosity of one or the other, the two may be made to appear equally bright on the two portions of the retina. Adopting this plan, and taking the mean of a large number of readings, it was found, to the writer's eyes, that the relative sensitiveness for *white light* of the centre of the retina, and of a spot 10° outside the axis, was as 37 to 33. The areas of the two curves plotted from the direct and "10° outside" observations, when the same white light was employed, were as 167 to 156, which is a ratio very close to the above, and thus the ordinates of each of the curves may be taken to indicate the relative luminosities of the colours in the different regions of the spectrum, and they are shown thus in the tables given below. A reference to Chapter XII. on the extinction of colour, will show how necessary it is that in these observations the colour and white patch should be of equal size.

Luminosity of Colours on the Fovea Centralis.

There is another part of the retina on which, if the different colours fall, the luminosities may vary from either of the foregoing. The fovea centralis, it may be remembered, is a very small area lying in the middle of the "macula lutea," or yellow spot. It is usually supposed that the axis of the lens cuts the retina in this spot. In order to arrive at some idea of the luminosities of the different rays when they fall on this very small area, a white cube of $\frac{1}{4}$-in. edge was employed, and the colour and white light each occupied one half of one of the faces. The eye was kept 5 ft. from the small surface, and the comparisons made in the usual manner, except that one eye was kept closed.

Calculations from these observations point to the fovea being about one-sixth more sensitive to the D light than is the macula lutea. To the green and the blue, the fovea appears less sensitive than the macula lutea. If the luminosities be taken at a greater distance than 5 ft. from the eye, it will be found that the fovea is less sensitive to green, and more to red, than is shown in Table IV.

This may be verified by causing an image of a star to fall on the absolute centre of the fovea, and comparing the colour of an adjacent star with it. The colour of the two stars will be found to differ, even if in the telescope they appear the same.

Alternative Method of ascertaining the Luminosity of the Spectrum Colours.

There is an alternative method of making the luminosities equal with the spectrum colours. In the white beam may be placed sectors with fixed apertures, and

TABLE IV.—*Luminosity Curves.* (*Arc light crater, inclined carbons.*)

I.	II.	III.	IV.	V.	I.	II.	III.	IV.	V.
Scale Number.	Wave-Length.	Outside Yellow Spot.	Yellow Spot.	Fovea Centralis.	Scale Number.	Wave-Length.	Outside Yellow Spot.	Yellow Spot.	Fovea Centralis.
64	7217	...	...	...	32	4924	21	8·5	6·5
63	7082	...	1	...	31	4885	18·5	7	5·5
62	6957	1	2	2	30	4848	16·5	5·5	4
61	6839	2	4	4	29	4812	14·5	4·7	3·5
60	6728	3 5	7	8	28	4776	13	4	3
59	6621	7·5	12·5	15·5	27	4742	11·5	3·5	2
58	6520	12·5	21	24	26	4707	10·5	2·8	2 4
57	6423	19	33	37·5	25	4675	9·4	2·3	2·1
56	6330	27·5	50	60	24	4639	8·2	1·82	1 9
55	6242	35	65	77	23	4608	7·3	1·6	1·5
54	6152	43	80	90	22	4578	6·3	1·4	...
53	6074	52·5	90	97	21	4548	5·7	1·2	...
52	5996	61	96	100	20	4517	5	1·08	1
51	5219	71	99	100	19	4488	4·5	·94	...
50	5850	79	100	98	18	4459	4	·86	...
49	5873	84	99	95	17	4437	3·6	·78	...
48	5720	85	97	90	16	4404	3·1	·70	...
47	5658	83·5	92·5	85	15	4377	2·7	·62	·62
46	5596	81	87	79	14	4349	2·3	·56	...
45	5538	77	81	72·5	13	4323	2·1	·50	...
44	5481	72·5	75	66	12	4296	1·9	·45	...
43	5427	68	69	59	11	4271	1·65	·40	...
42	5373	62·5	62·5	51	10	4245	1·4	·34	...
41	5321	57	57	45	9	4221	1·2	·30	...
40	5270	52	50	40	8	4197	1	·26	...
39	5221	46	42·5	32	7	4174	·88	·22	...
38	5172	41·5	36	27·5	6	4151	·75	·18	...
37	5128	37·5	29·5	22	5	4131	·63	·16	...
36	5085	33·5	24	18	4	4106	·50	·14	...
35	5043	30	18·2	14					
34	5002	26·5	14·2	10					
33	4963	24	10·5	8·4					

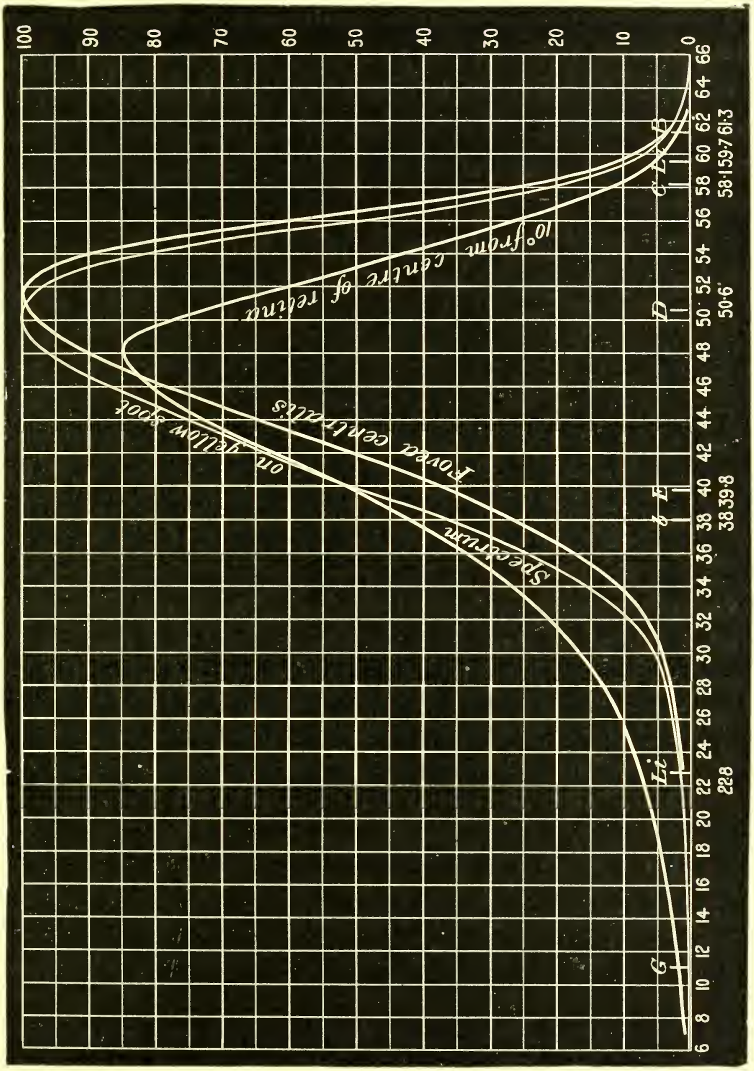

100
90
80
70
60
50
40
30
20
10
0
66 64 62 60 58 56 54 52 50 48 46 44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10 8 6
58·1 59·7 61·3
50·6
38 39·8
22·8
B
C
D
E
b
Li
G
10° from centre of retina
Fovea centralis
on yellow spot
Spectrum

FIG. 32.

the equality determined by moving the slit backwards towards the red and forwards towards the blue. Some ray between the maximum luminosity in the yellow and the extreme ends of the spectrum will be found which is of equal brightness to the white as diminished by the rotating sectors. There are, of course, two positions, one on each side of the yellow, which have equal luminosity.

The sector may be made of thin card, the alternate quadrants being cut out as shown in the figure (which

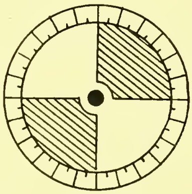


FIG. 33.

is one of a pair), and the rim should be correctly graduated. By this plan it is feasible to make the double aperture read 2°, and when one is covered up it will thus show 1°. These are angles so small as to preclude them from use with rotating sectors, which open and close at will during the rotation, owing to the existence of "backlash," as has already been said. For still smaller luminosities, resort must be had to the plane unsilvered mirror or to the annulus.

The following are the scale numbers, wave-lengths, and luminosities of the different fiduciary Fraunhofer and some bright lines. The luminosities are those found with the crater of the positive pole of the electric light, sloping carbons, *within the yellow spot* on the retina.[1]

[1] At pp. 244, 245 will be found the luminosity curves of the spectrum when formed with the arc light with horizontal positive pole; also for the Nernst light and for a paraffin light at page 251; Paper No. 4.

TABLE V.

	Scale Number.	λ	Luminosity.
B	61·3	6866	4
Li (red) . . .	59·8	6705	8
C	58·1	6562	17
D	50·6	5892	99·5
E	39·8	5269	48
b (Mg.) . . .	28	5183	36
F	30·2	4860	6
Li (blue) . . .	22·8	4603	2
G	11·1	4307	·6

Luminosity of a Spectrum produced by Feeble Light.

To ascertain the luminosity of a very feeble spectrum, a special plan has to be adopted. The comparison white beam should be introduced into the measuring box described at p. 148. In the measures made, and which are described, the D light when uninterrupted by the sectors, had a luminosity of $\frac{1}{132 \cdot 5}$ of an amyl lamp[1] at 1 ft. off at the end of the box. The beams from the spectrum were introduced into the apparatus so that the colour patch fell on S. The luminosity of the different rays was taken in the ordinary manner, interposing the rotating sectors in the reference beam. The following results were obtained (see Table VI.), the mean of the readings being given. Here we have a proof that the normal eye becomes insensitive to the red end of the spectrum when formed from a much-reduced intensity of white light. It must be remarked, however, that all colour was not entirely absent, though it was very considerably reduced in saturation. The measurements were made with some trouble at first, owing to the inclination

[1] An amyl lamp gives a light closely equal to that of a standard candle.

of the eye to direct its axis to some point other than the centre of the patch where the white strip and the colour strip touch one another. The diversion of the axis of the eye in some cases made the colour more luminous, and in other cases less, than it did when the eye was properly directed.

TABLE VI.[1]—*Luminosity of Spectrum Reduced in Intensity so that* $D = \frac{1}{132 \cdot 5}$ *Amyl Lamp* 1 *ft. distant.*

Scale Number.	Wave-length.	Mean Reading reduced to 100 Maximum.
56	6330	5·4
54	6152	5
52	5996	13
50	5850	24
48	5720	42
46	5596	66
44	5481	84
42	5373	95
40	5270	100
38	5172	94
36	5085	84
34	5002	72
32	4924	58
30	4848	45
28	4776	32
26	4707	23
24	4639	17·5
22	4578	14
20	4517	11
14	4349	5
10	4245	2·5

[1] These results and those on pp. 100 to 103 are to be found in Paper No. 4.

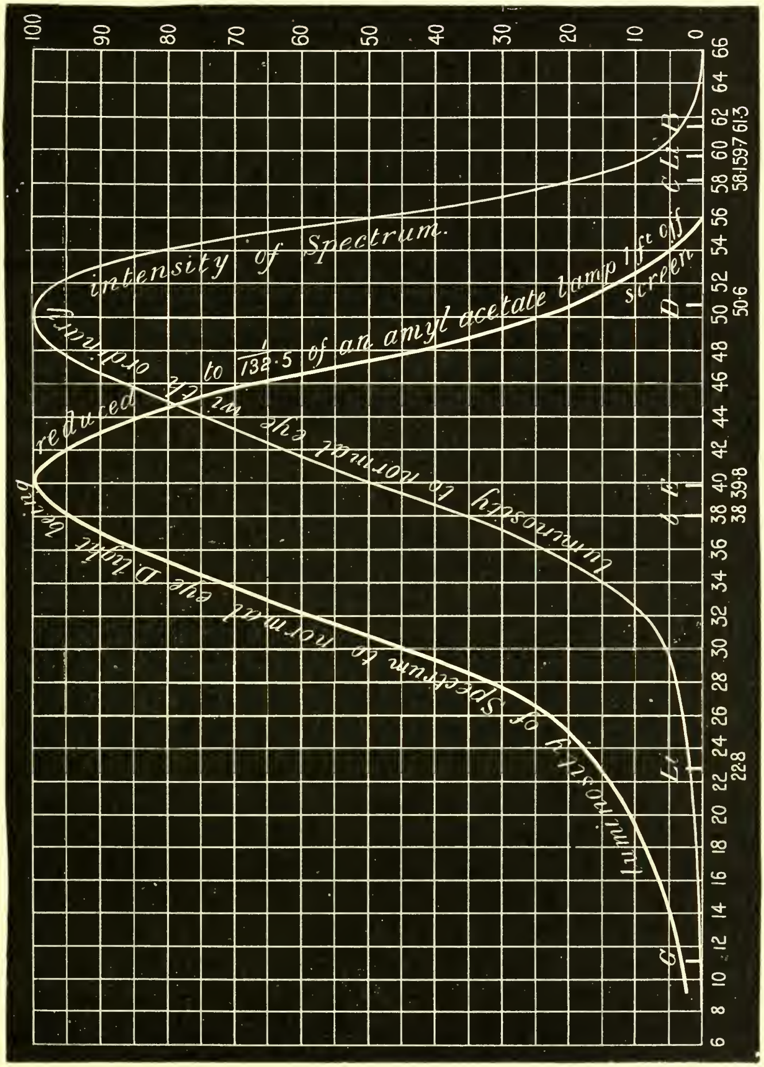

intensity of Spectrum.
luminosity to normal eye
luminosity of Spectrum to normal eye
reduced to 1/132·5 of an amyl acetate lamp 1 ft off screen
G
F
D
B
0
10
20
30
40
50
60
70
80
90
100
6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66
22·8
38 39·8
50·6
58·1 59·7 61·3

FIG. 34.

Relative Luminosity of Rays for Different Spectrum Intensity.

Having found from the curves that the relative luminosities of the rays of the spectrum when feeble differed from the same rays when bright, it became a matter of some importance to ascertain in what manner the relative luminosities of the rays varied when the intensity of the light which formed the spectrum *was altered in a definite ratio.* Evidently the most satisfactory method of ascertaining this was to throw a patch of white light on the screen and then to diminish its luminosity by known amounts, and, having selected some rays of the spectrum, to measure their luminosities. The box described at p. 148 was again brought into requisition. A beam of white light was caused to illuminate one half of the small white square screen at the end of the box, and the other half was illuminated by the ray whose luminosity was to be tried. Rotating sectors were placed in each beam; the apertures of those in the white were fixed at different angles, whilst those of the sectors in the coloured beam were opened or closed till the luminosities appeared the same to the eye, a series of readings being taken for each ray. The results thus obtained were plotted, and some typical rays are shown in Fig. 35. The ordinates are the apertures of the sectors which were placed in the path of the monochromatic rays, and the abscissæ the apertures of the sectors in the white beam. The tangent of the inclination to the vertical of the curve at any point therefore represents the ratio of the luminosities of the coloured to those of the white beam for known intensities of light. If this ratio were the same for all intensities, the curve would become a straight line

starting from the origin. This is only the case, it will

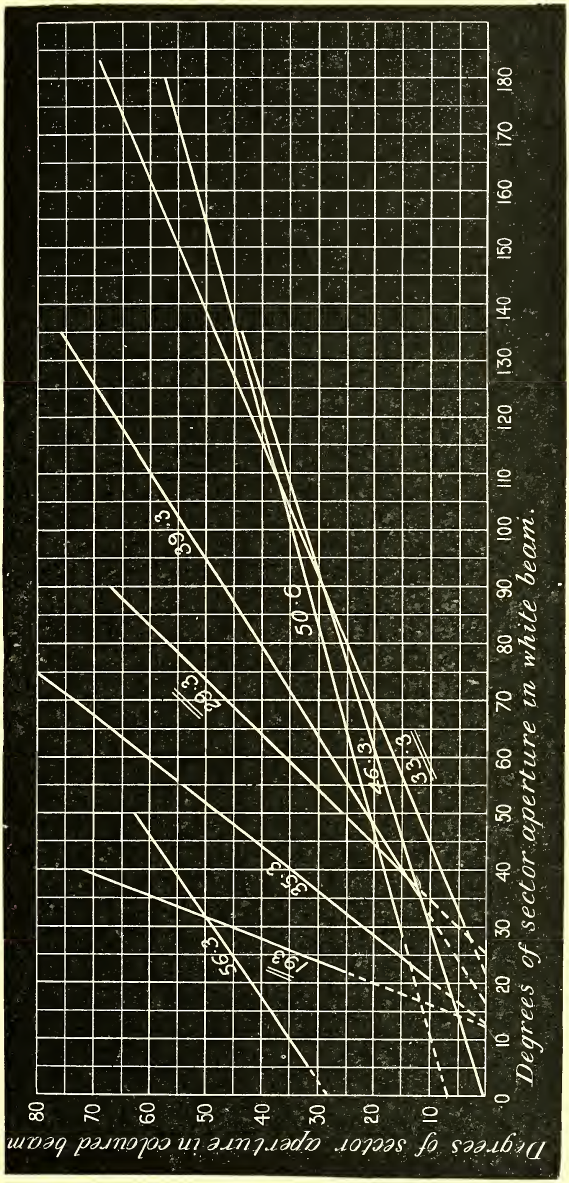


FIG. 35.

be seen, with one ray, viz. that at scale number 46·3,

or about λ 5618. This ray and white light would therefore be extinguished together.

It will be seen, however, from the diagram, that the other curves become straight lines when certain degrees of intensity, different in each case, are reached; and if these straight lines are produced to cut the axis, the ordinates of the rays which lie towards the blue end of the spectrum above 46·3 have a negative value at the zero of white light, whilst those which lie toward the red side of 46·3 have a positive value; showing that with rays of equal luminosity the blue part of the spectrum should be extinguished last, and the red part first; we shall see in Chapter XII. that this is the case.

It is, moreover, evident, and this has been demonstrated by experiments described above, that for low intensities of light the luminosity curves of the spectrum will vary as the intensity is increased, but that a degree of intensity is soon reached when all the curves in Fig. 35 become straight lines. The distances from the origin where the lines are curved are so small compared with the distance where the curves of all the rays become straight lines, that the relative luminosities of the different rays in spectra of ordinary intensity are practically the same. In the experiments last described, the D light on the screen when not reduced by the sectors was equivalent to ·027 of a candle at 1 ft. This would bring it far beyond the point where its curve, and indeed those of all other rays, would become straight lines.[1]

[1] It must be remembered that we are only dealing with light reflected from a white screen, and it does not follow that the lines may continue straight indefinitely when the light is of the brilliancy seen when looking direct at a bright spectrum, such as that of the sun, with a fairly wide slit to the collimator.

The following table shows the agreement of the results of these last measurements with those of the observations, from which the luminosity curve for the central part of the eye was constructed. The quotient of the difference of two abscissæ in the straight part of each curve divided by the difference of the corresponding ordinates evidently is the tangent of the inclination to the vertical, which, as stated above, is a measure of the luminosity of the corresponding ray. In Column IV. of the table, the first five of these quotients are multiplied by 28·2 in order to make the maximum luminosity 100. In the case of the last three entries in the table, the beam of white light had necessarily to be diminished in intensity before it passed through the sectors, and to bring the luminosities to the same scale the tangents had only to be multiplied by 5·03.

TABLE VII.—*Relative Luminosities of Rays.*

I.	II.	III.	IV.	V.
Scale No.	Wave-Lengths.	Tangent of Inclination.	Tangent × 28·2 or 5·03.	Luminosity of Normal Curve.
56·3	6358	1·5	42·3	43·5
50·6	5889	3·5	98·6	99·5
46·3	5618	3·16	88	88
39·3	5246	1·55	43·7	44·5
35·3	5066	·77	21·7	20·2
33·3	4975	2·39	12	12
29·3	4822	·96	4·9	5
19·3	4497	·33	1·68	1·5

Luminosity of Spectrum of Light of Low Grade.

Should the luminosity of the spectrum of artificial lights of low grade be required, we have to proceed

somewhat differently. Let us suppose that we wish to ascertain the luminosity of the spectrum of the brightest part of the flame of a paraffin lamp. In this case we form a smaller prismatic spectrum, using perhaps only one prism, and do not use a camera with its lens, but only a lens of slightly shorter focus to throw the spectrum on a white card. This must take place in a darkened room, and the top of the spectrum must fall on a finely-divided scale of $\frac{1}{2}$ mm. An image of the paraffin light is thrown on the slit of the collimator, which it should fill; a thin knitting-needle, mounted on a small leaden base, is placed near the screen in the spectrum; a thin strip in the spectrum is cut out and appears black. A comparison light—that emitted by a part of one of the legs of an incandescent light—illuminates this shadow. The alterations in the brightness of the comparison lights may be effected by the graduated annulus which has already been described. The two shadows thrown by the spectrum and the comparison light by the intervention of the needle are made to touch one another. The luminosity of the part of the spectrum measured is that which touches the shadow illuminated by the comparison light. Care must be taken that the brightness of the spectrum is not of such a nature as to allow it to come into the category of a feeble spectra of which the relative luminosities of the rays differ (as we have seen at the beginning of this chapter) from those where it is fairly bright. By using a wide slit in the collimator and a short spectrum, this can always be effected. The measures are not quite so exact as when a colour patch is employed, but the mean of repeated readings will give results which are sufficiently close to the truth.

Sum of Separate Luminosities Equal to the Combined Luminosity.

In the early measures of luminosity,[1] it was proved by repeated measures that the luminosity of a mixed light is equal to the sum of the impression of each of the components. To test the illuminating value of colour mixtures, three slits were placed in the spectrum, in the red, green, and violet. The luminosities of the rays coming through each were measured—(1) separately; (2) in pairs; (3) the whole combined. The measures then made were on a different scale of units to those at present employed, but they are none the less comparable.

TABLE VIII.

	Observed.	Calculated.
R	203	204·25
(R+G)	242	241·75
G	38·5	37·50
(G+V)	45	46·00
V	8·5	8·5
(R+V)	214	212·5
(R+G+V)	250	250·25

Combining these together we get—

$$\begin{aligned} R+G+V &= 250 \\ (R+G)+V &= 250{\cdot}5 \\ (R+V)+G &= 252{\cdot}5 \\ (G+V)+R &= 248 \\ (R+G+V) &= 250 \\ &= 250{\cdot}25 \text{ by least squares.} \end{aligned}$$

Various other measures with slits at different parts of the spectrum were made, and all went to prove the correctness of the assumption made.

Within the limits of error of observation the lumi-

[1] See Paper No. 2.

nosity of the combined spectrum measured as white equals the luminosity of spectrum colours measured separately, the slit in the spectrum being of accurately measured width. In order to make this measurement, it became necessary to reduce the luminosity of the recombined spectrum colours, so that the white reflected beam which was used in measuring the separate spectrum colours might be utilised.

A carefully graduated fixed sector with 10°, 13°, and 5° double apertures was rotated in the spectrum, and with these reduced intensities of the white patch formed by the recombined spectrum a match was made with the reflected white light of the colour patch apparatus. The luminosity of the ray of maximum intensity, SSN. 50, was also measured. Knowing the area of the curve obtained by the measurement of the rays in the different positions of the accurately measured slit H (p. 41), the result, as already indicated, showed that the area of the luminosity curve was equal to the luminosity of the white of the combined spectrum.

[The above results were obtained whether the annulus or the sector was employed, and whether the reduction in intensity of the recombined spectrum white was effected by glasses of different densities of black placed in the spectrum or by the sector with fixed aperture.]

Flicker Luminosity.

When obtaining the luminosity of different parts of the spectrum as it appeared to those colour blind, who could only undergo a brief examination, it was suggested by Dr. Watson, F.R.S., that perhaps the measures obtained by the flicker method might give similar results to the luminosity method and probably

be less difficult to a person wholly untrained in making observations. The flicker method is dependent on the fact that when a colour and (say) a white are alternately brought on to a screen, following one another with great rapidity, there is a sensation of flickering of the light. When one or other of them is reduced in brightness, a stage is reached in which the flickering gives way to a quiescence, and no real flicker is observed. According to some writers, this absence of flicker enables the luminosity to be determined. Thus if a green be observed on a small screen for a fraction of a second, and immediately succeeding it a white is shown for the same length of time, and again the green is observed to be followed once more by the white, and so on, the probability is that the alternations of colour and white will give a distinct flicker. If by some suitable means the luminosity of the white be increased or diminished, at some stage in the alteration of the brightness of the white the flickering will cease and the small screen will show a mixture of the green and white in a state of quiescence. The brightness of the white, when this occurs, is held to give the luminosity of the green. We shall see shortly that the brightness by the flicker method is not exactly the same as that obtained by the shadow method, but, as used by us, the former is capable of conversion into the latter without any appreciable error.

Flicker Apparatus.

Dr. Watson's flicker apparatus is shown in the accompanying illustration (Fig. 36). It is so constructed and placed that the beams of light do not overlap but follow one another without any dark or overlapping interval between them.

The figure will give an idea of the complete apparatus as designed by him. S is the white square of magnesium carbonate on which the colour and the white light are alternately thrown. AAA is an iron band attached to a disc of sheet-iron, D, extending round half the circumference. BB is a similar band on the other side of the disc, also extending round the other half of the circumference, as shown. It will be noticed that where one band ends on one side of the disc

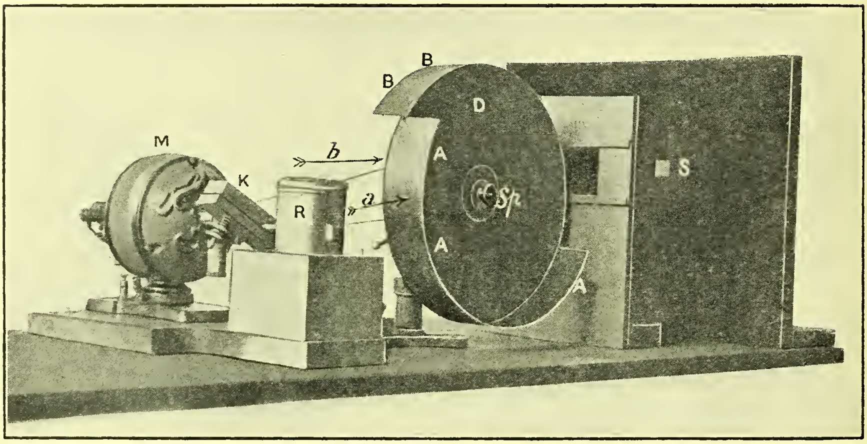


Fig. 36.

the other begins, so that beams of light which fall on AA and BB respectively can be caused to fall alternately on the white square S. The arrows *a* and *b* show the direction of the two beams. The disc is caused to rotate round its centre, S*p* (a spindle), which is connected with a pulley (not shown), and this is connected with a small motor, M, to which a brake, K, is attached. A speedometer, R, also registers the speed of rotation. The white light is admitted to the A side and the coloured beam to the B side. It is placed between the recombining lens and the screen.

It is obvious that in using this flicker apparatus the reduction of the luminosity of the white light could not be effectively made by the rotating sectors, since it itself would cause a flicker. Recourse was therefore made to an annulus, described at page 72, placing its slit, through which the beam has to pass, in the path of the reflected beam of white light, where the rays from the lens cross in forming the white image of the first surface of the first prism. At this point there is an image of the slit of the collimator. The slit in front of the annulus is opened fairly wide so as to include the whole of the beam.

When using this apparatus the rotation of the flicker wheel should be of such rapidity as to speedily obtain a cessation of flicker. Experience has shown that revolutions of 560 to 600 per minute are speeds which for a fair intensity of spectrum suffice in the red, yellow, and green. When the less bright portions of the spectrum (*i.e.* the blue and the extreme red) are under measurement, the speed may well be reduced to 400 per minute. There is another point to remember, viz. that there is a zone of brightness in which no flicker is seen. In the bright part of the spectrum this zone is very small and is rarely above 2° of the annulus used, but in the weak intensities it may be as much as 10°, or even as much as 20° when the brightness is very small. For this reason measures should include alternate observations made first with the white too bright and next with the white too feeble for the flicker to be absent. The limits of the "non-flicker" zone are thus determined and the mean of the readings may be taken as the place of minimum disturbance.

The following is a curve obtained from a spectrum in which the D light was one candle at 1 metre distant from the screen. The spectrum itself was formed

from the crater light of an electric arc, in which the positive carbon was horizontal. The current was 18 amperes, and gave a light rather bluer than that given at p. 94. The patch of colour and white was received on a slab of compressed carbonate of magnesia. The side of the square was closely 1 in., and the observations were made with the eye at a distance of 3 ft. from it. To compare with this flicker curve, the curve of luminosity obtained in the ordinary way is given. The bright-

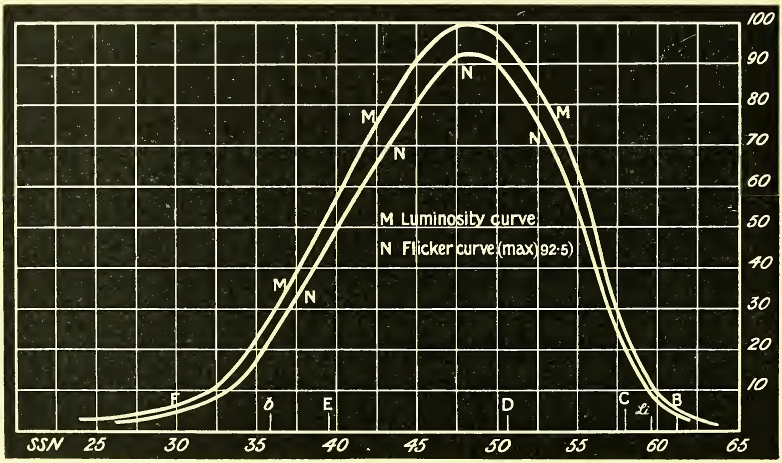


Fig. 37.

ness of the maximum at SSN. 48, as given by the flicker and the shadow method, the two having been taken without altering any of the apparatus, was found to be, flicker to luminosity, as 92·5 to 100. In order therefore to correctly estimate the difference between the results obtained by the two methods, the ordinates of the flicker curve should be reduced to $\frac{92 \cdot 5}{100}$ of the value shown. This indicates that a difference exists between the luminosities obtained by the two methods.

Table IX.—*Comparative Flicker and "Shadow" Luminosities of the Light from an* 18-*ampere current Horizontal "Positive" Carbon of an Arc Light.*

SSN.	Flicker Luminosity. Max. = 100.	Flicker Luminosity. Max. = 92·5.	Shadow. Max. = 100.
64	...	...	·5
62	3·2	2·96	2
60	8·5	7·86	8·7
58	23	21·3	21·6
56	47·5	43·9	48·3
54	70	64·7	70
52	86	79·55	84·7
50	97·5	90·2	96·2
48	100	92·5	100
46	91·3	84·35	95
44	78·5	72·61	85·3
42	66·2	61·23	72
40	52·7	48·75	56·1
38	38·7	35·8	41
36	24·3	22·5	27·5
34	12·8	11·84	15·8
32	7·7	7·12	8·9
30	5	4·62	6·17
28	3·6	3·33	4·6
26	2·8	2·59	3·5
24	...	...	2·7
22	...	...	2·16
20	...	...	1·76

It should be here stated that the results obtained by the flicker method[1] are with most eyes difficult to obtain satisfactorily beyond SSN. 26 towards the violet, the width of the "non-flicker" space being very wide, and it may be wrong to assume that the true non-flicker took place exactly at the centre of such a band.

[1] It must be remembered that it is only flicker against white that has here been measured. The flicker of a coloured ray against the different rays of the spectrum do not give the same flicker luminosities.

CHAPTER IX

COMPLEMENTARY AND CONTRAST COLOURS[1]

When one colour, "optically" mixed with another colour, makes white (or grey when colour discs are used), these colours are said to be complementary to one another. Before, however, colours can be said to be complementary, we have to know the quality of the white they match when mixed. The white of daylight or of the arc electric light, we know, requires a certain amount of some blue ray to be added to the yellow-orange of the "D" light to match the white of either of these sources, but the blue ray which has to be taken will not be exactly the same in the two cases. When, however, the match is complete, the two pairs are complementary to one another, and they will be complementary whether one or both be diluted with the white light which has to be matched. If, however, we take an extreme case of finding the complementary to the orange when the so-called white light is that of a paraffin lamp, candle, or of an ordinary carbon filament glow-lamp, we are met with a difficulty. The hue of any of these lights can be very closely matched by orange rays in the spectrum. Evidently, then, in such a case there can be no complementary to this orange. We know, of course, that these lights contain all the spectrum colours, and amongst them, of course, those of higher refrangibility, such as the blue rays, but the general mixture of them does not enable the eye to distinguish the light from the spectrum colour with any degree of exactitude.

[1] Paper No. 11.

One way of ascertaining exactly complementary colours is to place three slits in one spectrum, and make a match in hue with the ray from a second spectrum whose complementary is sought.[1] The hue may be readily obtained by mixtures when the slits are placed at the red lithium line, the magnesium "b" line, and the blue lithium line, or when the third slit is placed well in the violet. If the D light is matched, the mixture will be slightly paler than the single ray, owing to a certain amount of white light which is inherent in the green ray.[2] (The cause of this white light being found in the green ray will be gathered after reading Chapter XV., in which the method of finding the colour sensations throughout the spectrum is described.) When the hue is obtained, the white light for which the complementary is to be sought should be thrown on the cube surface in the colour patch apparatus, and after noting the width of slits which give the match for the ray, the slits are brought into position again by means of the scale, and are again opened or closed until the match to the white is made. The widths of the slits are again measured, and from these two sets of measures the width of slits required for the complementary colour can be calculated. Suppose we take an example of the D light. The width of the slits were found to be—

Red Slit.	Green Slit.
100	25

When the white, for which the complementary colour to be matched was that of electric light, the following were the width of slits used :—

Red Slit.	Green Slit.	Violet Slit.
250	100	110

[1] A convenient plan is to use the modified apparatus given at p. 44.

[2] White is also in the blue ray if that be used, though it is not found if the third slit be in violet.

Making the red slit readings equal in both cases, we get for the D light—

Red Slit.		Green Slit.
100	+	25

and for the white light—

Red Slit.		Green Slit.		Violet Slit.
100	+	40	+	44

The complementary colour to the D light is therefore—

Green Slit.		Violet Slit.
15	+	44

The slits can be set at these numbers, and the complementary colour is reproduced, and this can be matched with a ray coming through a single slit in the second spectrum. When found, its scale reading is noted, which if necessary is converted into the wave-length. This is a more roundabout way than the following. When two spectra are produced in the same apparatus (the "scaling" of both being accurately made), the ray to which the complementary is required can be thrown from one spectrum on to one half of the surface of the cube, the white, which the ray and its complementary when mixed are required to match, is thrown on the other half, using, of course, the rod to make the shadows touch just in the middle of the square surface. From the second spectrum a ray may be thrown on to that half which is occupied by the colour. By trial, the particular ray which matches the white with it, altering the widths of the slits when necessary, is readily found. The scale number of the second spectrum is noted and converted where necessary into its wave-length.

When the complementary to a colour for an artificial light is required, the same procedure may be adopted,

using, instead of the white reflected beam of the arc light, the artificial light to illuminate one half of the cube's surface.

When only one spectrum is available, two slits may be placed at varying distances apart (the distance apart being measured by reading the scale number when the D light passes through each slit). The slide is then moved in the spectrum till a position is found by trial where the mixed colours match accurately the white which is being used. The scale number is read off, and the positions of the slits in the spectrum is thus known. [Of course, when the slide in which the slits are fixed is graduated to correspond with the transparent scale, as it is in the writer's instrument, the distance apart of the centres of the slits can be read off without resort to the reading of the D light passing through the slits. When one slit is kept in a fixed position and only the second one moved, the reading of the scale number when the match is made determines the position the slits occupy in the spectrum, if the scale number is once determined when the D light passes through the fixed slit.]

Simultaneous Contrast Colours.

When two colours are viewed side by side, as, for instance, when two strips of different colours fall on the surface of the cube from the colour patch apparatus, both colours may appear to be altered in hue. The change induced is caused by the simultaneous contrast of the two colours. When one of the colours is white, the change in colour is most marked, as it changes its hue in a remarkable and (to most eyes) unexpected manner. When measuring or observing colours which are in juxtaposition, it is sometimes difficult to determine

whether the hue is real or whether it is produced by contrasts. Artists are well aware of the value of these contrasts. If a very vivid red is required in a picture, he will manage to place a green near the red, and this brightens the colour. Contrasts with colour and white are much more recognisable when the two do not exactly touch one another, but are separated by a mixture of the two. Suppose the colour patch is in use and that one of the spectrum colours is on the screen, with the white superposed. If a thin rod be placed in the paths of the two beams, there will be one shadow illuminated by the colour and the other by the white, and intermediate between the shadows will be a mixture of the colour and white. The white will show the contrast, taking hues of very varying nature, according to the spectrum colour contrasted with it. In the following table an endeavour has been made to give names to the contrasts as seen by a normal eye when the white is (1) that of the arc light, and (2) that of gas light:—

Contrast Colours.

Uncontrasted Spectrum Colours.	Contrast Spectrum Colours.	Contrast White in Electric Arc Light.	Contrast Spectrum Colours.	Contrast White in Gas Light.
Red	Cherry red	Green-grey	Cherry red	Green-grey
	Scarlet	Bluish green-grey	Scarlet	Sap green
Orange	Terra cotta	Blue-grey	Light red	Green-grey
Yellow	Raw sienna	Light blue-grey	Olive green	Pinkish grey
Yellow-green	Olive green	Umber	Apple green	Dark mauve
Green	Emerald green	Pinkish lavender	Emerald green	Pink terra cotta
	Grass green	Light pink	Emerald green	Pink terra cotta
	Blue-green	Dark pink	Blue-green	Pink terra cotta
	Signal green	Salmon	Peacock blue	Salmon
Blue-green	Cyanine blue	Yellow ochre	Prussian blue	Reddish yellow
Blue	Violet blue	Brownish yellow	Violet blue	Brownish orange
	Blue violet	Dark greenish yellow	Blue violet	Brownish yellow
Ultra marine	Ultra marine	Raw sienna	Ultra marine	Raw sienna
Violet	Violet	Burnt sienna	Violet	Yellow ochre

All the contrast colours given by the whites are pale colours, and by no means saturated. It is often asserted that the colours in the white evoked by contrast with the spectrum colours are the complementary colours mixed with white. We shall show that such does not appear to be the case.

Before proceeding further, it may be useful to record the changes in hue which are evoked by contrasting different colours together. The following table will give an idea of the changes that take place :—

Original Colours.		Change due to Contrast.	
Red	Orange	Red becomes yellower	Orange becomes green-grey
,,	Green	,, unaltered but brighter	Green unaltered but brighter
,,	Blue	,, becomes more orange	Blue becomes greener
,,	Violet	,, ,, orange	Violet no marked change
Green	Orange	Green becomes bluer	Orange becomes yellower
,,	Blue	,, ,, olive	Blue becomes more violet
,,	Violet	,, ,, yellower	Violet becomes bluer
Orange	Blue	Orange becomes redder	Blue becomes deeper
,,	Violet	,, ,, greener	Violet becomes bluer
Violet	Blue	No marked change takes place in either	

To obtain this table, observations were made with the double colour patch apparatus. Slits were placed in four places in the first spectrum and in the same positions in the second spectrum, viz. in the red, orange, green, and violet. The contrasts in most cases were very marked, as could be seen by causing the same colours to fall on a white screen outside that on which the observations of contrast were made.

Reverting to the contrast colours on the white, the following arrangement was at first made. Two separate colour patch apparatus were employed, the receiving screens (the faces of white cubes) being placed about 1 ft. apart. Later the experiments were made by

utilising the double spectrum apparatus (p. 44), which formed the necessary two spectra and gave also the white light required. We will call the left-hand spectrum No. I., and the right-hand one No. II.

With No. II. instrument the colour contrast was formed between white and a spectrum colour. The colour emerged through a slit placed in the spectrum and forming a patch on the cube, and the white was that reflected from the first surface of the prism. A thin rod $\frac{3}{8}$ in. diameter placed in the paths of the two beams caused two shadows to be cast on the cube, one illuminated by pure white light and the other by the spectrum colour. These were separated from one another by an interval illuminated by a mixture of the spectral colour and white light, and on each side of the shadows the same diluted colour was to be found. The appearance of the side of the cube (called No. II.) was as below.

A was a stripe of white light, B of colour, *c c c* of the same colour diluted with white. The intensity of the D sodium light thrown on the surface was ·5 of a candle at 1 ft. distance; the intensity of the other colours can be obtained from the luminosity curve at p. 94.

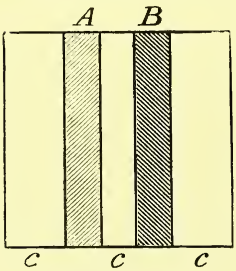


Fig. 38.

The patch of colour from instrument No. I. was thrown on the face of a second cube (No. I.) 1 ft. away from the first cube, and was used to match the contrast colour produced on A, Fig. 38. The beam of white light, which was nearly equally divided between the first and second spectrum by means of the bundle of glasses (see p. 39), also fell on the face of this cube. The intensities of the colour

and white could be altered at will; that of the colour by opening or closing the slit through which the colour came, and that of the white light by rotating sectors. By this means the dilution of the colour could be secured. (It may be mentioned that the effect of using a strip of the face of this last cube equal in width to the width of A was tried, but no advantage over using the entire surface of the cube was found.)

The method of procedure was as follows. With instrument No. II. the colour to be used and the white beam were thrown on the face of the cube No. II., the luminosities of the two being made as nearly equal as possible. With instrument No. I. a colour, which it was judged was nearly the dominant colour of the contrast colour of A, was thrown on the face of the cube No. I. and white light added. When a match was perfected by slight changes in the colour and in the intensity of the added white, the scale number of the colour was read, from which the wave-length could be determined, and the relative luminosities of the white and the colour were measured. The luminosity of the D light with a slit of known aperture had been determined. Hence in repeating an observation it was only necessary to read the apertures of the slit and of the sector.

It was found that a slight change in the contrast took place after repeatedly shifting the eyes from the one cube to the other. For instance, the contrast caused by green appeared to lose a little of its red hue, degenerating into a brown-yellow. To get rid of this difficulty an artifice was employed, which appeared to be completely successful. An ordinary box stereoscope, with the lenses removed, was mounted on a stand, and in such a position that when the left eye only saw cube

No. II., the right eye saw only cube No. I. Thus, the right eye never saw the contrast colour, whilst the left never saw the match. In this way, by alternately changing the direction of the eyes to the two cubes, a match could be readily made. When the match was considered satisfactory, both eyes were directed to a moderately weak white light, and, after a short interval of time, turned to the two cubes, when, if the contrast colour on the one cube and the mixed colours on the other appeared to match accurately, the necessary readings were taken.

Subsequently it was found more convenient to move the rod placed in the paths of the two beams of the

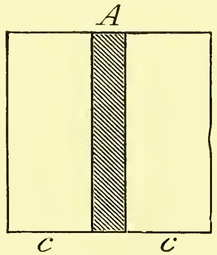


Fig. 39.

instrument No. II., so that only one shadow appeared. In Fig. 39 the stripe of white light, A, is shown, and *c c* are spaces on each side of A illuminated by the colour mixed with the white. (It is obvious that the stripe of colour could be equally well isolated.) *There is no difference in the contrast colours created in the white by this plan*, showing that the presence of the saturated colour is not necessary to give the full contrast. This is a very significant fact, and may help to throw a light on the cause of the contrast. The following table gives the results of both sets of observations, as the results are the same.

TABLE X.—*Diluted Background.*

Colour Contrasted with White.				Colour Produced by Contrast.		
SSN.		Wave-length of Colour.	Luminosity in terms of one Candle at a foot off.	SSN.	Dominant Wave-length of Contrast Colour.	Proportion of White to Colour. White=1.
Red	57·9	672	·15	29·4	483	·054
	56·3	636	·22	29·8	484	·057
Orange	53·6	612	·44	29·9	485	·066
	51·8	598	·46	30·7	487	·070
Yellow	50	585	·50	28	481	·100
	47·5	569	·49	26·8	471	·120
Green	45·7	558	·44	51	610	·165
	42·7	541	·33	51·4	598	·165
	38	517	·13	51	592	·170
Blue	33·6	499	·07	50·4	587	·175
	29	481	·023	50	585	·200
	24·5	466	·012	49·8	583	·250
Violet . . .		All violet	...	49·5	581	·300

It will be seen from the table that different and representative parts of the spectrum were used, being the red, yellow, green, blue, and violet, and that in every case the contrast colours provoked in the white could be matched by a single colour of definite wave-length when diluted by white light. If the contrast colour caused by the green were its complementary diluted by white light, it should be by a purple, which requires a mixture of red and blue, whereas it is an orange. The fact as to whether the contrast colour as matched could ever make white when mixed with the colour which caused it was very readily proved. The two colours were thrown on the same cube, and the proportions of the colours altered. In some few cases there was a very close approximation to the formation of a white which matched the electric light, but in the majority no match could be made.

Another set of experiments further exemplified this. In instrument No. II. three colours were chosen—one in

red, another in the green, and the third in the violet. The same three colours were found in instrument No. I., and three adjustable slits placed in each of them. With these three slits a match in the first instance was made with the white of the electric light—a contrast between white and the red was then formed on the cube, illuminated by No. II. instrument. The red was then shut off from instrument No. I., and the mixed violet and green lights were diluted with white light, but in no state of dilution did the white stripe as coloured by contrast appear of the same tint as the complementary colour of the red as obtained from the diluted mixture. The same negative results were obtained by making the contrast with the green. With the violet a much nearer approach was made.

This experiment was varied by matching the light from an Argand gas burner, and forming the contrasts by means of the same quality of light. The same negative results were again obtained.

The difference, if any, was next observed between a contrast made by a saturated colour and that given by the diluted colour.

In order to get a stripe of white enclosed between two saturated stripes of colour, a Vernon-Harcourt screen was employed instead of a rod (Fig. 40). The principle of this may not be known generally, so a brief description of it may be necessary. It consists of a thin rectangular metallic plate of about two inches wide, in which two broad slits, A and B, are cut and separated from each other by C, the width of the slits. This plate, if placed in the path of the beam, allows two stripes of colour and of white to pass. By carefully adjusting the

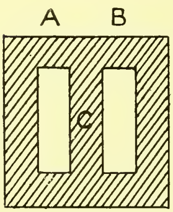


Fig. 40.

position of this screen, a stripe of white may be enclosed between two stripes of colour. The results are given in Table XI.

TABLE XI.—*Saturated Background.*

Colour Contrasted with White.			Colour Produced by Contrast.		
SSN.	Wave-length of Colour.	Luminosity in Terms of Candle Power.	SSN.	Dominant Wave-length of Contrast Colour.	Proportion of White to Colour. White=1.
57·9	672	·15	28·7	481	·015
56·3	636	·22	30·1	485	·020
53·6	612	·44	30·7	486	·022
51·8	598	·46	30·75	487	·024
50	585	·50	31·6	491	·025
47·5	569	·49	59·8	671	·035
45·7	558	·44	53·5	611	·052
42·7	541	·33	51·8	598	066
38	517	·13	50·7	590	·066
33·6	499	·07	50	585	·066
29	481	·023	49·8	583	·068
24·5	466	·012	49·7	582	·070
	All violet		49·3	580	·070

The contrasts with gas light, using the same light to dilute a spectrum colour in instrument No. I., were also measured, and these are given in Table XII.

TABLE XII.—*Contrasts in Gas Light.*

Wave-length of Colour.	Dominant Wave-length of Contrast.
636	485
585	590
558	598
499	592
465	589
All violet	588

There are such small differences in the wave-lengths of the contrasts produced by the diluted and saturated

colours that it may be presumed they are due to error of observation, although each table is derived from the mean of several observations extending over a period of three years. It may be interesting to state that in every case the extremes in the one series embraced the mean value tabulated in the other series, and that in no case did the mean differ from any single observation more than λ 2·5.

There is, however, a very simple means of noting the accordance between the contrasts caused by the diluted and saturated colours. With one instrument the contrast caused by the saturated colour can be shown on one surface, and with the other the same colour, but diluted, on another surface, so that the two can be directly compared. To the eye the only difference between the two was in the amount of dilution of the colour produced by contrast; otherwise they appeared absolutely identical.

An endeavour was made to ascertain at the same time what dark interval between the white and the colours would prevent the contrast being appreciable. To do this a cube with a whitened surface was placed as shown on the top of another white surface with a black interval between the two (Fig. 41).

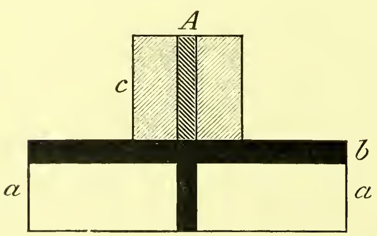


Fig. 41.

The colour patch was thrown so as to fall only on the cube *c*, whilst the white beam illuminated the white surface *a* as well. When the white beam was also thrown on another cube a foot away it was practicable to form an idea of the colour of *a*. The effect was curious and interesting. When the black band *b*

was just $\frac{1}{4}$ in. in depth, the eye being distant 4 ft. from the cube, the white stripe A appeared strongly coloured, *a* appeared *very nearly* white, and if by an artifice saturated colour surrounded A, it was pure white. If black intervals separated the white A from the diluted colour *c*, the colour in A did not disappear; it appeared to be more diluted, but the colour still remained. If, however, a black interval was on only one side of A (that is, by placing the shadow against the edge of the square and making the black interval between the colour and A), when the colour was saturated the white appeared perfectly white, whilst if dilute just a shade of contrast colour was visible.

By placing a diluted coloured space in contact with a pure white space which was in its turn in contact with a saturated colour, it became possible with several colours to make the diluted colour appear white in contrast to the contrast colour itself. With red this became impracticable.

CHAPTER X

NUMERICAL REGISTRATION OF COLOUR

It will be gathered that a colour is known when its hue, its purity, and its luminosity are known. This applies not only to the spectrum colours, but also to the colours of objects in nature. It is to these last that we will apply ourselves first. Suppose we have to ascertain what is the spectrum colour which matches a piece of brown paper. This can be done in the following way. Place three slits in the spectrum, one in the red, another in the green, and the third in the blue. Fasten a piece of brown paper on half of the receiving cube surface, and then illuminate it with the white light in which it has to be viewed, and by a rod or rods cut off the spectrum colours from it, and, shielding the other half (a white surface) in the same way, we can then make a match to the paper by opening or closing the three slits. The apertures of these slits are measured, and the strip of brown paper is replaced by a white surface, which again is matched by the three slits, and their apertures also measured.

Let the first be—

$$\begin{array}{ccccc} \text{Red.} & & \text{Green.} & & \text{Violet.} \\ a & + & b & + & c \end{array}$$

and the second—

$$a' + b' + c'$$

we can tell which colour is smallest in the first, and we shall in this case find it is in the violet.

Taking the same proportions of each colour in the first equation which exist in the white, we get the brown paper colour made up of two equations: red, green, and white.

Let a'' b'' be the proportion of red and green necessary to make a white with c; then the first equation becomes—

$$\overset{\text{Red.}}{a''} + \overset{\text{Green.}}{b''} + c = \text{white},$$

and

$$\overset{\text{Red.}}{(a - a'')} + \overset{\text{Green.}}{(b - b'')} = \text{brown paper, less the white in } a.$$

We therefore have the colour of the brown paper a mixture of the red and green. Closing the slits of the red and green to the apertures $(a - a'')$ and $(b - b'')$ respectively, we make a mixture which matches the brown paper in all respects except in its purity (mixture with white). Using the double apparatus, we can move a slit along the second spectrum, which will match in colour the brown (less the white), and will be found to be in some cases an orange (with other descriptions of brown paper a yellow). The ray which matches the colour of the brown paper (− white) is called its dominant colour. When extreme accuracy is required, it may be that resort must be had to the methods indicated in Chapter XVI. In that chapter it is shown how from the equation alone the true dominant colour may be arrived at.

Using a Single Slit to obtain the Dominant Colour.

Instead of using three slits in the spectrum, from what has been said it will be seen that only one slit

need be employed together with the means of mixing white light with the colour. In practice this is the best arrangement for rapid determination of the dominant colour.[1] The colour patch apparatus given on p. 39 is employed, using the mirror $G^{\prime\prime\prime}$ for obtaining the white light which is required as an addition to the colour. The slit is moved in the spectrum till a position is found in which the hue is presumably correct. White light from the plane reflected beam is then added until the hue is proved correct nearly. If there is some small inaccuracy, the slit is slightly altered in position, when the match by means of white is again tried. A few trials may be necessary to get a perfectly good match. When the colour is found, its luminosity and that of the added white are measured, and the colour of the pigment, or the light transmitted through a coloured transparent medium, is then registered as a mixture of the dominant colour of a certain luminosity, together with an added white luminosity. The only case in which this plan will not answer is when a purple has to be registered. There is no spectrum colour which can match such a colour with any amount of white added. In such a case resort must be had to the three-slit method, and the colour registered in terms of the complementary colour and white. The writer had submitted to him for such registration a certain number of signal glasses and coloured pigments, and the annexed tables will give an idea of the use to which this method may be put.

[1] Paper No. 13.

Glass.	Electric Light.			Gas Light.		
	Dominant Colour, λ.	Percentage of White in Colour.	Luminosity (White =100).	Dominant Colour, λ.	Percentage of White in Colour.	Luminosity (Gas light =100).
Railway Company's red light .	6250	7	10·4	6275	...	13·1
Another Company's red light .	6200	...	10·4	6200	12	13
,, ,, ,, .	6250	...	9	6275	...	10
Railway Company's signal green	4925	46	21·8	5070	50	18·1
,, ,, ,,	4925	38	16·2	5050	34	12·5
,, ,, ,,	5100	61	19·2	5170	62	19 4
Maker's signal green . .	4925	24	7·6	5050	22	6·9
Bottle-green glass . . .	5500	32	9·1	5320	50	10·6
Cobalt-blue glass . . .	4675	38	4·4	4650	59	3·3

Colour.	Dominant Colour, λ.	Percentage of White Light.	Luminosity (White=100).
Vermilion	6100	2·5	14·8
Emerald green	5220	59	22·7
French blue	4720	61	4·4
Brown paper	5940	50	25
,, ,, (greyer) . .	5670	67	19·5
Orange	5915	4	62·5
Chrome yellow	5835	26	77·7
Blue-green	5005	42·5	14·8
Eosin dye (*Sporting Times*) .	6400	72	44·7
Cobalt	4820	55·5	14·5

It must be remembered that the above are colours which vary in composition, and they are only given as specimens of the manner in which they can be registered.

The pure colours of the spectrum cannot as a rule be matched by the three-slit method, since, as we shall see in Chapter XVI., there will be an excess of white in the mixture compared with that of the ray which is to be matched.

CHAPTER XI

COLOUR DISCS

The problem of the mixture of colours would be incomplete if no reference were made to the mixtures which can be made by the rotation of colour discs in which different colours are shown as sectors. It is proposed to show that the same effect can be produced by passing successive images of the colours rapidly before the eye as if the colours were thrown one upon the other.

Let us place a cell containing a solution of a purple colour such as permanganate of potash (to which no single ray of the spectrum can make a match even with the addition of white light) in the path of the white reflected beam. We may place one slit in the red of the spectrum and the other in the blue, and by opening or closing the slits make an accurate match of the purple colour on the white surface of the cube.

Fig. 42.

Let us next cut out a cardboard disc as shown in Fig. 42, in which the angular apertures are all exactly equal, and rapidly rotate it round its centre in front of

the two slits so that the red only passes through one pair of apertures and the violet through the other. No rays will pass through the outside and inside apertures at the same time. On rotation it will be seen that the purple has precisely the same hue as before, though of course dimmer. The match will be apparent if a sector is placed in the white beam. The effect of two colours falling intermittently, but for equally short intervals, on the eye is the same as when the intermittence is absent and the coloured lights are mixed. This is due to the persistence of the light on the retina, as explained in Chapter III.

The image caused by the red light does not fade away before the blue image is impressed, and the compound impression gives the same sensation of purple as is given by the absolute mixture of the two lights on the cube's surface.

For experiments in colour, this duration of impressions is of great value. We can take advantage of it to compound the colours of pigments together in a very simple manner. For instance, we can paint a circular disc blue and red as shown, and by causing it to rotate round its centre a purple will be produced. A small electromotor similar to that used for making the movable sectors rotate, having a bouche, screw, and nut at the end of the spindle, will be found convenient for making these experiments. The discs, perforated with a clean-cut hole, can be slipped over the spindle, and rest against the bouche. The nut will clamp the disc and cause it to

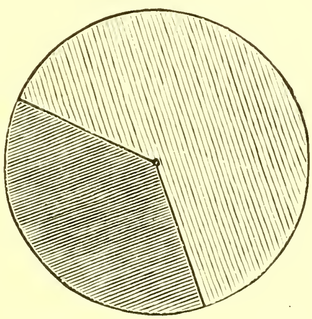


FIG. 43.

rotate with the spindle, and the colours on the disc will then blend.

The motor shown in the figure will enable the discs to be rotated sufficiently rapidly for the colours on discs 8 in. in diameter to blend. It must here be stated that the brighter the light that is thrown on the discs,

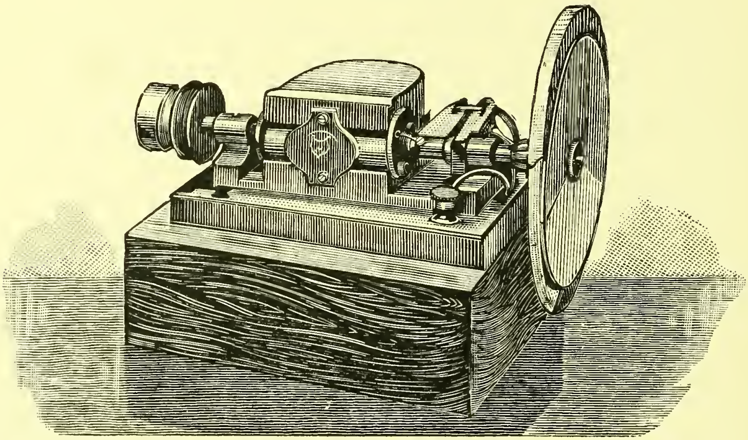


Fig. 44.

the more rapid their rotation must be. Very convenient discs for producing mixtures of colours by rotating discs are a red (vermilion to which a trace of blue is added), an emerald green, and a French ultramarine blue. Let us call such a red R, the emerald green G, and the ultramarine U. A white disc we will call W and a black X.

A convenient diameter for the colour discs with such an electromotor as shown is 6 inches, and for the black and white 8 inches.[1]

[1] Small discs of, say, 2 inches diameter on thin card may be painted with different coloured sectors, and if a pin be passed through their centres a smart movement of the finger at the periphery will cause them to rotate sufficiently rapidly to cause the colours to blend without flickering.

The discs should be of stout unglazed paper or of thin card, and should present even surfaces of coloration. Their centres should be pierced with a clean-cut hole the size of the spindle of the motor, and a cut should be made from the circumference to the centre as shown. This enables the different discs to be interlocked. As many as five colours with varying sector apertures can be shown at one time. The white disc should be a disc painted with zinc white, held together by the minimum of white gelatine or fish glue (see p. 46). The amount of white light reflected from the black (which should be ivory black and spread as paint with the aid of the colourless size) must be determined, the measurement being that given by light falling nearly perpendicularly on the surface.

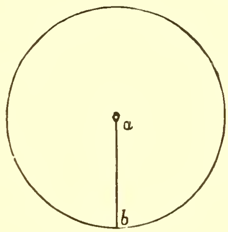


FIG. 45.

The examination of the colours of the discs must be thorough if quantitative work is required from their mixture.

In the first place, the measurement of the intensity of spectrum colours reflected from the discs themselves (or from portions of the painted paper or cards out of which the discs were cut) must be made by one of the methods given in Chapter VII. (pp. 79–84); and afterwards the luminosity of the same colours can be measured directly or can be calculated by means of the luminosity tables (see p. 94). [Table XXXVIII. would have to be used for finding the white impurity mixed with the dominant colour. The dominant colour may not really be that which matches the colour in the spectrum, for, as shown elsewhere (p. 320), some colours have a yellower hue by mixture with white.]

Before entering into the more elaborate measures to

which colour discs can be put, it is proposed to give their simpler uses, and this will be done by an excerpt from the writer's book, *Colour Measurement and Mixture.*[1]

"If we wish to produce a white, or rather a grey, from three colours, we can take three small discs of V (vermilion), E (emerald green), and U (French ultramarine) of equal diameter, and behind them place interlaced discs of black and white of larger diameter, rotating the whole five on a common centre. We shall find that by altering the proportions of the first three, we can get a grey which can be exactly matched by a mixture of black and white, X and W. It has already been shown that even lampblack reflects a certain amount of white light, so this amount of reflected white light has to be added to the white in the outside sectors. In the sectors used it was found that the following proportions of the three colours were required :—

$$\begin{aligned} V &= 124 \\ E &= 143 \\ U &= 93 \\ \hline &\,360 \end{aligned}$$

and to make the same grey it required—

$$\begin{aligned} X &= 278 \\ W &= 82 \\ \hline &\,360 \end{aligned}$$

Now the black reflected 3·4 per cent. of white light, so that really the proportions of black and white were—

$$\begin{aligned} X &= 268{\cdot}6 \\ W &= 91{\cdot}4 \\ \hline &\,360{\cdot}0 \end{aligned}$$

[1] *S.P.C.K.*

"These matches were made in the light emitted by the crater of the positive pole of the electric light, and are correct only for this light. The greys here are dark greys, and such greys can be matched exactly by throwing the white light in which the comparisons were made on a white card [in a dark room] by means of rotating sectors. We can prove whether our matches are fairly correct from our previous measures of the luminosity of these three colours in comparison with that of white. The luminosities of V, E, and U, as found from measures (given *ante*, white being 100), are 36, 30, and 4·4. 124 of V would have a luminosity $\frac{124 \times 36}{360}$ or 12·4; 143 of E would have 11·92; and 93 of U would have 1·14, which added together give a luminosity of 25·46. The luminosity of $\frac{91 \cdot 4}{360}$ of white (which is from the mixture of black and white), comes to 25·39, so that we may assume our observations have been fairly correct." If the rotating discs be moved into any other light, the matching of the greys will not be exact. Again, colours in the outer discs may be matched with V, E, U, X, and W as inner discs. The colour which has to be matched may possibly require X and W with it.

It may seem curious that X and W may have to be added to the three colours in the inner discs, but a little reflection will show why it is. Suppose we want to know the composition of gamboge (Y) in terms of the V, E, and U, we have a large disc of the Y and also large discs of X and W. On rotation we shall find that no U is required in the inner discs, and that the general hue of the gamboge can be obtained by V and E rotating. Mix these two in any proportions we like,

we shall find that the mixture will never attain the luminosity of Y; consequently we must darken Y with X. Even then we shall find that the rotating V and E will always be a little less saturated in colour. This means that on rotation V and E produce a certain quantity of white light mixed with the yellow they make. This necessitates adding some white to the rotating disc containing X and Y, and finally we shall get a match—

$$\overset{\text{V}}{172} + \overset{\text{E}}{188} = \overset{\text{Y}}{75} + \overset{\text{W}}{45} + \overset{\text{X}}{240}$$

This equation tells us one or both V and E are impure colours containing white, and that they contain between them at least $\dfrac{45 + \frac{240}{100}3{\cdot}4}{360} = \dfrac{53}{360}$ of white.

Further, it tells us we can obtain the luminosity of Y, as we know those of V and E as given in the previous example, viz. 36 and 30 respectively, white being 100. This makes the luminosity of the left-hand number of the equation $17{\cdot}2 + 15{\cdot}67$ or $32{\cdot}87$, and the right-hand number $\frac{75}{360}\,Y + 14{\cdot}76$. Consequently—

$$\frac{75}{360}\,Y = 32{\cdot}87 - 14{\cdot}76 = 18{\cdot}11$$

—that is, the luminosity of Y is 86·9.

In an ordinary way we can find the luminosity of a pigment of any colour by replacing it for either V, E, or U.

Taking as an example an orange disc (O), the red (V) had to be removed, and was replaced by O. A match with the grey was made and found to be—

$$\overset{\text{E}}{115} + \overset{\text{U}}{150} + \overset{\text{O}}{95} = \overset{\text{W}}{83} + \overset{\text{X}}{277}$$

Knowing the luminosities of E and U, that of O is determined—

$$\frac{115\times 30}{360}+\frac{150\times 4{\cdot}4}{360}+\frac{95}{360}O=\frac{83}{360}+\frac{3{\cdot}4\times 277}{360}$$

$$95\ O=5319$$

$$\text{or } O=56$$

These are examples of the simpler uses of colour discs, but a further extension can be made by the measurements which were suggested at the beginning of this chapter. In the foregoing nothing is known about the three colours employed, except that they are scarlet, green, and blue, and all other pigment colours are referred to them in that limited capacity. We shall show in a subsequent chapter how discs can be used to replace spectrum colours in a great many instances.

When the illuminating source of light is a large surface, such as the sky, the method before described is more difficult to apply.[1] It may be requisite for some purposes to use such a source, as, for instance, when one has to find a suitable coloured screen for making a photograph giving the various colours of objects as seen in daylight in their proper luminosities in black and white. It then becomes necessary to devise a plan by which rings of different colours can be made of equal luminosity in ordinary daylight by rotating them with the proper proportions of black. The rings must be concentric and rotated round the centre (see Fig. 46). The problem to solve is to ascertain what amount of black ought to form part of each ring to make the luminosities equal.

[1] Paper No. 14.

In Chapter VIII., p. 101, it is shown that only one ray of the spectrum, a greenish yellow, progresses in luminosity at the same rate as white light. Thus, if part of a white screen be illuminated by this colour and another part by white light, and the luminosities are equal (say, to one candle), then if the two beams are equally diminished they will still match in lumi-

FIG. 46.

S is the nut of the spindle.
V is a violet disc (methyl violet).
B is a portion of a blue ring (French ultramarine).
R ,, ,, red ring (vermilion).
G ,, ,, green ring (emerald green).
Y ,, ,, yellow ring (chrome yellow).
W ,, ,, white ring.

nosity until the light is so feeble that it ceases to stimulate the retina. Other rays lying not far from this ray, both on the red and green side of it, give practically the same results. When, however, the red is compared with the white, each being made equal (say, to one candle), equal diminution of the beams will not show the luminosities as remaining equal, for the red

becomes rapidly less luminous than the white. With the blue-green, the blue, and the violet, the reverse is the case, the white becoming darker than the colour as the beams are equally diminished.

Further, it is shown in Chapter XII. that colour disappears from all rays of the spectrum long before (except in the case of the pure red) their *light* is ex-

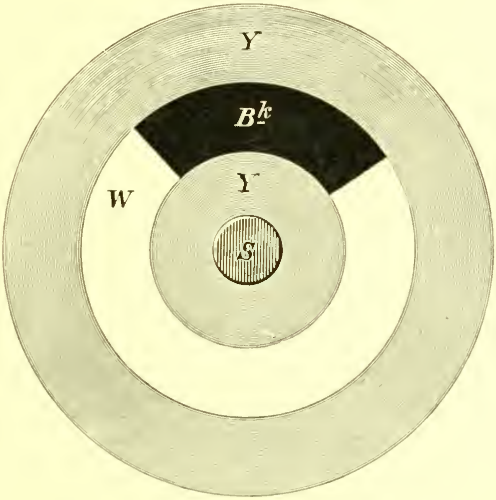


FIG. 47.

YY are yellow discs.
B^k is a black disc.
W ,, white disc.
S is the nut of the spindle.

tinguished, this last owing to the feeble stimulation of the retina. Naturally, as the colour begins to disappear, the matching of the luminosity of the ray under consideration with that of white will become easier to carry out.

These facts make it possible to devise a ready method of ascertaining the luminosity of any colour.

If we take two yellow discs, one (say) 8 in. in diameter and the other 4 in., and between them sandwich a pair of interlaced black and white discs of 6 in. diameter, and rotate the four discs on a rotating machine at a speed which will make the black and white into a grey without scintillation, this grey can be made, by altering the proportion of black to white, to match the luminosity of the yellow. A very exact match can be obtained by observing the discs through a black transparent medium, such as the black obtained on a photographic plate after development with methol or amidol developers. The deposit may be so dense that the yellow colour may practically disappear, and the two dull greys may then be readily matched. The luminosity of the yellow in terms of the white is given by the angle which the white subtends when the small proportion of white reflected from the black is added to it.

The same procedure may be adopted for a green colour and its luminosity be obtained. Four or five observations for each colour should be made.

When the luminosities of these two colours have been determined, 4-in. discs of them may be interlaced with a blue, and a grey formed, which can be matched with a grey formed of black and white as before. From the angles which the sectors of the colours subtend and of the black and white employed, the luminosity of the blue can be calculated. The luminosity of the blue being ascertained, a red disc may be interlaced with the green and the blue disc, and that of the red calculated. As a check, a black and yellow disc may be interlaced and compared with the colour given with the red and green discs inter-

laced, one of the pairs of course being of greater diameter than the other.

To ascertain what degree of accuracy could be attained, the following experiment is given in detail. The light used was the arc light, and the measurements as described above made.

It was found that the black reflected 3·33 per cent. of white light, and that when the luminosity of the yellow was matched the interlaced black and white discs occupied 82° and 278° respectively of the compound disc. This gave the yellow a luminosity of 78, white being 100. In a similar way, the luminosity of the green was found to be 43. These two discs were interlaced with a dark blue disc and a grey formed which matched a grey formed by black and white. The following equation was obtained :—

$$\underset{\text{Yellow.}}{118} + \underset{\text{Green.}}{71} + \underset{\text{Blue.}}{171} = \underset{\text{White.}}{122} + \underset{\text{Black.}}{238} = \underset{\text{White.}}{130}$$

Yellow.

The luminosity of $118 = \frac{118}{360}$ of $78 = 25·6$.

Green.

The luminosity of $71 = \frac{71}{360}$ of $43 = 8·5$.

White.

The luminosity of $130 = \frac{130}{360}$ of $100 = 36·1$.

Blue.

The luminosity of 171 is therefore represented by—

$$36·1 - (25·6 + 8·5) = 2$$

The luminosity of the blue pigment is therefore—

$$\frac{360}{171} \text{ of } 2 = 4{\cdot}2$$

The luminosities of the three pigments were then compared with that of white by the method described at p. 87, and found to be—

Yellow . . .	77·7
Green . . .	43·2
Blue	4·1

The luminosity of the blue only differs from that found by the new plan by 0·1.

The red disc was then interlaced with the blue and the green, and a grey formed as before, and from calculation it was found that it had a luminosity of 32·5. Direct measurement made the luminosity 32·7.

Having obtained the luminosity of the three standard colours, that of any other colour can be calculated by substituting for one of them a disc of such colour, and again making a grey and matching it with a grey formed by the black and white. This method can be carried out in any light, whether candle light, electric light, or daylight; but the luminosities of the colours will vary with the kind of light employed.

When the luminosities of the colours are determined, the angles which the segments of the rings in Fig. 46 should subtend can be calculated after taking into account the luminosity of the black employed.

(Each ring when rotated being equally luminous, an appropriate screen, placed in front of a photographic plate, will show equal density for each part of the developed image of the disc. All objects photographed through such a screen on similar plates will be rendered in proper gradations of light and shade regardless of colour.)

PART II

CHAPTER XII

EXTINCTION OF COLOUR AND LIGHT [1]

It is a matter of everyday experience that the colours of nature are seen at their best when daylight or sunlight is brilliant, and that as the day wanes most coloured objects lose their colour and have a tendency to become grey. After the sun has set, the colour of light-hued flowers, for instance, rapidly lose the delicate hues. A red rose will become almost black, green leaves will become grey; a scarlet-coloured brick will become dark, losing its ruddiness. In these changes of the quality of the rays reflected from the different objects, there are evidently two phenomena which are more or less mixed up together: (1) the loss of colour; (2) the loss of light itself. Investigations into these phenomena must evidently form part of experiments in colour vision which have to be carried out in the laboratory, more particularly when quantitative measures have to be undertaken.

We again naturally turn to the spectrum as the best source of colour, and light with which the scientific investigation should be made. If the conditions under which the extinction of either light or colour from the different rays of the spectrum can be ascertained, it will be comparatively easy to apply the results to the rays reflected from coloured objects. In this chapter it is proposed to start with the extinction of colour, and to commence by describing some simple experiments which

[1] Papers Nos. 4, 7, 24, and 26.

will enable us to realise under what conditions the sense of colour is lost.

Using the colour patch apparatus, let us place three slits in the spectrum—one in the red, another in the green, and the third in the violet. By substituting a compounded lens in place of the recombining lens, we can form three coloured patches side by side. (To make this compound lens, it is convenient to take an ordinary spectacle lens of the same focus as the recombining lens, and to divide it into three sections. As in Fig. 48, a diamond can be used to cut the sections A, B, C as shown. The three portions are then re-arranged and mounted in a wooden frame, as shown in Fig. 49. The three sections of the lens are placed as shown, the thinnest parts of A and C being next to B in order to have the optical centres of the three some small distance apart.) Any of the three coloured images can be increased or diminished in luminosity by adjusting the widths of the slits. In the experiment to be performed the red patch should be made decidedly brighter than the green patch, and the green than the violet. Between the slit of the collimator and the lens forming the image of the crater is placed the graduated annulus.

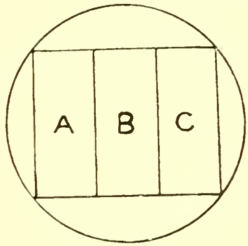


Fig. 48.

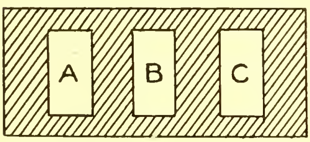


Fig. 49.

The light getting to the collimator slit passes first of all through the thinnest part of the annulus. The red patch will still appear brighter than the green, and the green than the violet. In the darkened room the annulus is turned so that the white light forming the three

patches is gradually diminished. As the light gets feebler, the red patch loses its luminosity more rapidly than the green, and the violet also becomes enfeebled. By turning the annulus, the light becomes so dimmed that the red patch disappears altogether, whilst the green and violet patches become dull and colourless. Here we have an example of the total extinction of light and colour in the red, and the extinction of colour only in the green and the blue.[1]

Another striking experiment is to remove the slide carrying the slits, and to place a lens of about 10-in. focus in front of the collecting lens. This will form a brilliant spectrum on a white screen (placed where the square patches of light are generally received). Using the graduated annulus as before, in front of the collimator slit, the spectrum can be gradually weakened by interposing its thicker parts. The red will appear to close towards the green, as will also the violet. When the thickness interposed is still further increased, the red will disappear altogether, and the yellow and blue will follow, so that finally we have a grey patch left, where with the bright spectrum there was bright green.

Another illustrative lecture experiment is to place one slit in the spectrum about the red lithium line and another near the E line in the green. The patch on the screen will be a yellow formed by the mixed light after adjusting the width of the slits. The annulus can again be employed to diminish the light entering the slit of the collimator until a grey patch is produced. The "red" slit can be closed altogether without apparently altering the colour or luminosity of the patch. On increasing

[1] This experiment illustrates what is called the Purkinje effect. It need scarcely be said that all these experiments have to be carried out in a darkened room.

the light, the patch will be only the green component of the mixed light. These experiments will have shown qualitatively that both light and colour can be extinguished.

We will now proceed to show how the point of extinction of the colour of all rays first of all can be determined. This can be best done by comparing a patch of white with a patch of colour and reducing the luminosity of the latter till it matches the white, when it also is reduced to about the same luminosity as that to which the colour has been reduced. A box, as shown in Fig. 50, about 3 ft. long, is required. The lid can be removed, so that if necessary S can be viewed with both eyes. At one end of the box, shown in plan, is an eye-piece E. The other end has at its centre a patch S, $1\frac{1}{2}$ in. square, whitened with zinc oxide, the rest of the inside of the box being blackened. The monochromatic beam a coming from the spectrum, and the reference beam b, are reflected by *plain* glass mirrors M_1 and M_2 to apertures T^I and T^{II} in opposite sides of the box, and from just inside these apertures, by right-angled prisms P^I and P^{II}, so as to fall on and cover S. Rods R^I and R^{II} are inserted in the box in the paths of the beams so that they illuminate opposite halves of S. Diaphragms inside the box cut off any stray rays of light, and rotating sectors placed at A and B regulate the strength of the beams. [It has been found perhaps more convenient, instead of the sector A being in the path of the coloured beam, to have an annulus in front of the spectrum slit, and only to have the sector B to control the white beam.] The room containing the apparatus is darkened. The sectors A are closed or the annulus is turned until no colour is discernible in the monochromatic beam, whilst the intensity of the white beam regulated by the sector B

gives the standard of whiteness to which the coloured beam is to be reduced. It is worthy of notice that when the white beam is entirely cut off, or made

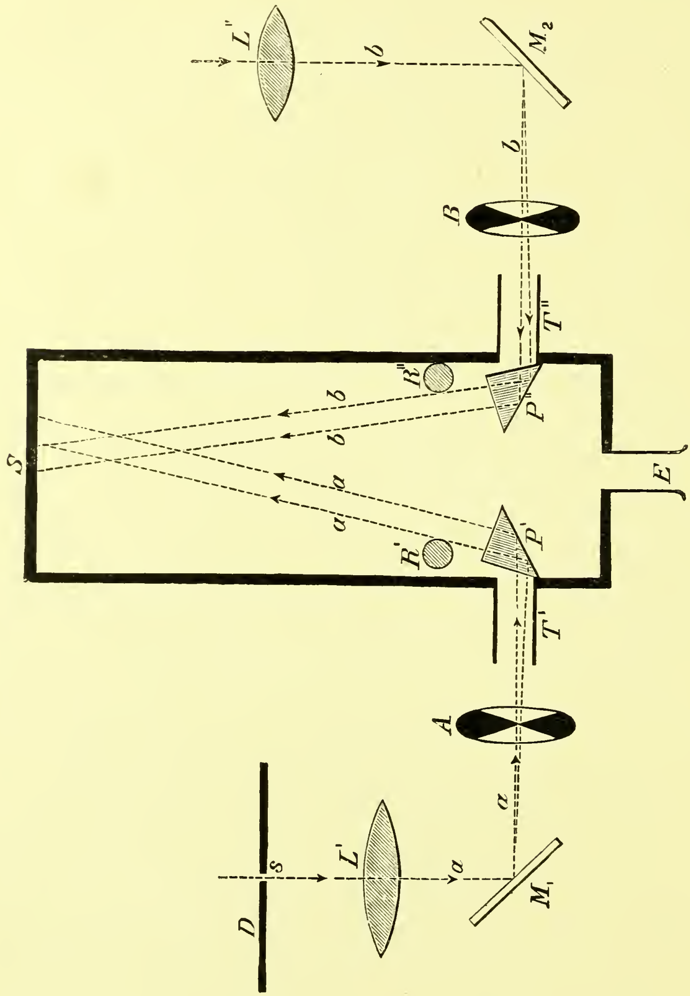


FIG. 50.

very feeble, colour often seems absent from the monochromatic light, but is again perceived when the beam is brightened. This is especially the case with the red part of the spectrum. The strength of the

coloured beam was therefore always reduced to the point that no colour was apparent whatever was the strength of the white beam. The apertures of the sectors (or, if the annulus is used, its scale) are noted for each colour. The direct measurement of the luminosity of such a feeble light would be very difficult; it was therefore determined in the following manner. The box and sectors were removed, and a white screen was placed at the same distance from M that S was. The slide carrying the slit in the spectrum was also removed so that a patch of white light was received on the screen; the luminosity of this was measured by direct comparison with an amyl-acetate lamp. The mirror M_1 was next removed, and the beam then fell on the screen of the original apparatus. Its luminosity was then compared with the reference beam. The slit slide being put back in the spectrum, the luminosity of the D light was measured against the same comparison light. The proportion that the luminosity of the D light bore to the recombined white patch was thus determined. As the value of the white light reflected from M to the end of the box was known from the first observation, the luminosity of the D light so reflected was calculated. The luminosity of the D light having been found, that of all the other rays was calculated from the luminosity curve derived from observations made with the central portion of the retina (see Table IV.), as it was with this part that the observations now being described were made.

The actual value of each ray when the colour disappeared was calculated from the aperture of the sectors, or the scale of the annulus.

The two tables and Figs. 51 and 52 show the luminosity of each colour of the spectrum to two different

TABLE XIII.

I. Scale No.	II. λ.	III. Luminosity of Spectrum of Normal Brightness.	IV. Reduction required for Colour to Disappear when D=1 Candle.	V. Reduction required when every Colour has a Luminosity of 1 Candle.
62	6957	2	·075	·0015
60	6728	7	·023	·00161
58	6521	21	·008	·00168
56	6330	50	·0035	·00175
54	6152	80	·0017	·00136
52	5996	96	·0014	·00136
50	5850	100	·0016	·0016
49	5783	99	·0025	·0025
48	5720	97	·0074	·0072
47	5658	92	·0061	·0056
46	5596	87	·0034	·00295
44	5481	75	·0027	·00202
42	5373	62·5	·0023	·00144
40	5270	50	·0019	·00095
38	5172	36	·0017	·00061
36	5085	24	·0018	·00043
34	5002	14·2	·0025	·00035
32	4927	8·5	·0036	·00031
30	4848	5·7	·0049	·00028
28	4776	4	·006	·00024
26	4707	2·8	·0075	·00021
24	4639	2	·0105	·00021
22	4578	1·4	·0165	·00023
20	4517	1·1	·024	·00026
18	4459	·86	·032	·000275
16	4404	·7	·043	·000301
14	4349	·56	·054	·000302
12	4296	·45	·07	·000315
10	4295	·34	·095	·000332
8	4198	·26	·13	·000328
6	4151	·18	·17	·000326
4	4106	·14	·24	·000336

persons when the hue becomes that of the comparison white. The amount of reduction[1] for each ray is recorded which was required supposing the light of D had a luminosity of one candle at 1 ft. off the screen. This

[1] In both cases the standard annulus was used for the reduction.

is shown in column IV. In column V. is shown the reduction that would be required supposing *each ray*

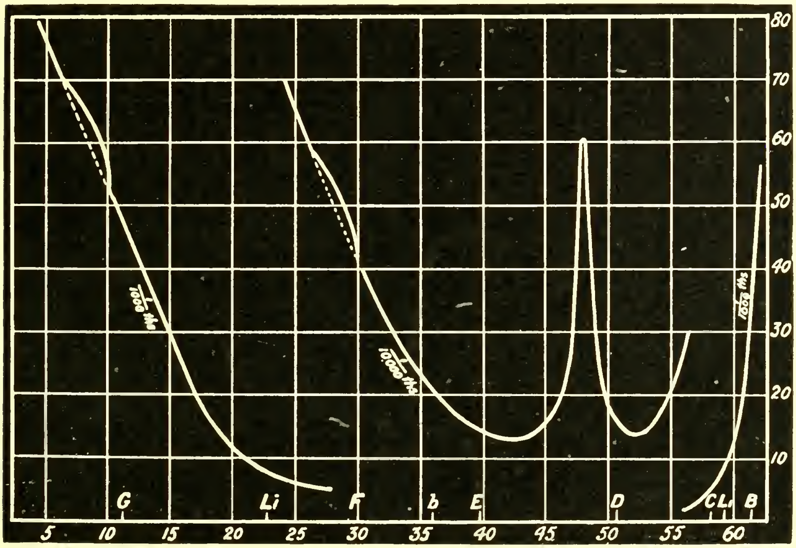


FIG. 5~~1~~. 2

had a luminosity of one candle at 1 *ft. distant from the screen.*

The following shows part of a series of readings, and is given to illustrate the closeness of the different observations made:—

Scale No.	Readings of the Annulus, in Degrees.							Mean of Readings, in Degrees.
62·7	35	40	36					37
60	145	135	130	130				135
57·35	197	198						197
54·62	230	250	240					240
51·95	250	235	255	248				247
50·87	235	238	250	230	235	248		238
50·33	230	227	250	255	262			245
48·25	163	172	180	190	190	190		183
47·63	221	228	220					223
45·47	230	243	245	250	225	245	255	241

Table XIV.—*W.'s Curves.*

I. Scale No.	II. λ.	III. Luminosity of Spectrum.	IV. Reduction required for Colour to Disappear when D=1 Candle.	V. Reduction required when every Colour has a Luminosity of 1 Candle.
62	6957	2	·056	·00112
60	6728	7	·014	·00098
58	6521	21	·005	·00105
56	6330	50	·0028	·0014
54	6152	80	·0017	·00136
52	5996	96	·0013	·00125
50	5850	100	·0017	·0017
49	5783	100	·0027	·0027
48	5720	97	·006	·00582
47	5658	92	·0032	·00294
46	5596	87	·0018	·00156
44	5481	75	·0014	·00105
42	5373	62·5	·0013	·00081
40	5270	50	·0014	·0007
38	5172	36	·0017	·00061
36	5085	24	·0021	·0005
34	5002	14·2	·0025	·00035
32	4924	8·5	·0033	·00028
30	4848	5·7	·0043	·000255
28	4776	4	·0052	·000208
26	4707	2·8	·0058	·000162
24	4639	2	·007	·000136
22	4578	1·4	·008	·000112
20	4517	1·1	·011	·000121
18	4459	·86	·015	·000129
16	4404	·7	·023	·000161
14	4349	·56	·033	·000185
12	4296	·45	·043	·000203
10	4245	·35	·054	·000189
8	4198	·26	·065	·000169
6	4151	·19	·07	·000133
4	4106	·14	·08	·000112

In the case of the whole series of readings, the D light of the spectrum through the thinnest part of the annulus was 0·145 candle at 1 ft. off the screen. The mean readings were taken, and then, as before

stated, transformed into the result that would have been obtained if the D light had been one candle at 1 ft. from the screen. Several separate series were taken, and the mean of the means adopted for each scale number.

[The tables and diagrams show that the reductions in luminosity of the rays at each end of the spectrum

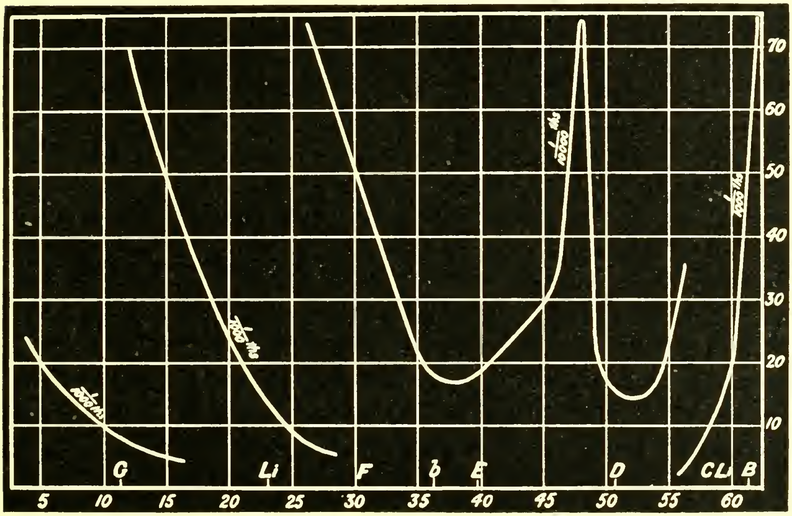


FIG. 52.

to match the white depends on the extinction of colour in one or more of the three sensations, and sometimes on the extinction of light in one of them (see Chapter XV.).] In the red, beyond Scale No. 58, the extinction of the colour of a luminosity of one candle at 1 ft. distant from the screen is affected when the luminosity is reduced to about 0·0016 candle, and the blue sensation is extinguished when its luminosity is reduced from one candle to closely 0·00009 candle. From observations made by a red blind person, it was found that the

extinction of a green colour only stimulating the green sensation was closely 0·0005 candle. The whole of the spectrum rays were matched with white by this observer, and in the green, of course, he matched a large portion with full white, or with very slight reduction in luminosity.

In the results just given, no mention was made as to the aperture which the patches of light subtended. Evidently an inquiry as to the loss of colour had to be made when the spot of colour subtended different angles on the retina. Perhaps a definite case will show such necessity. In moonlight the cherry-red of a brick wall will first be visible when standing 6 ft. away; but put a red wafer on a black or white background, and the red will have vanished if looked at the same distance away. In such a case as this, evidently the angular size of a coloured object has something to say to the results. The colour extinction box, when the writer made these experiments, was abandoned, and a different method employed, a dark room being used instead of the box. Two pieces of glass, each ground on both sides, were placed nearly in contact, strips of paper keeping them from absolutely touching. In front was a thin black board with two holes, a couple of inches in diameter, cut out, and the ground glass was placed behind these two apertures. Behind the board, and touching the ground glass, pairs of blackened thin brass diaphragms could be placed side by side. A very feeble white light from the crater of the arc light was caused to illuminate one of the apertures, whilst the colour under examination filled the other. The white and the colour were made of approximately equal luminosities. The colour and the white were darkened together by means of annuluses, and when the tints appeared to match perfectly, the diminution required was taken

TABLE XV.

Diameter of Aperture in Inches.	Angular Aperture.	Diameter in Powers of 2.	I.		II.		III.	
			Reading of Annulus.	Log.	Reading of Annulus.	Log.	Reading of Annulus.	Log.
0·94	1° 57′ 0″	– ·09	260	1·76	350	·99	300	1·42
0·724	1° 30′ 0″	– ·48	245	1·89	335	1·12	280	1·59
0·525	1° 5′ 0″	– ·93	220	2·11	310	1·33	260	1·76
0·35	43′ 43″	– 1·52	210	2·19	295	1·46	235	1·98
0·17	21′ 17″	– 2·56	170	2·54	255	1·8	205	2·235
0·086	10′ 46″	– 3·56	125	2·925	210	2·19	170	2·54
0·036	9′ 9″	– 4·81	75	3·355	155	2·66	120	2·97
0·012	3′ 3″	– 6·4	10	3·91	100	3·14	60	3·48

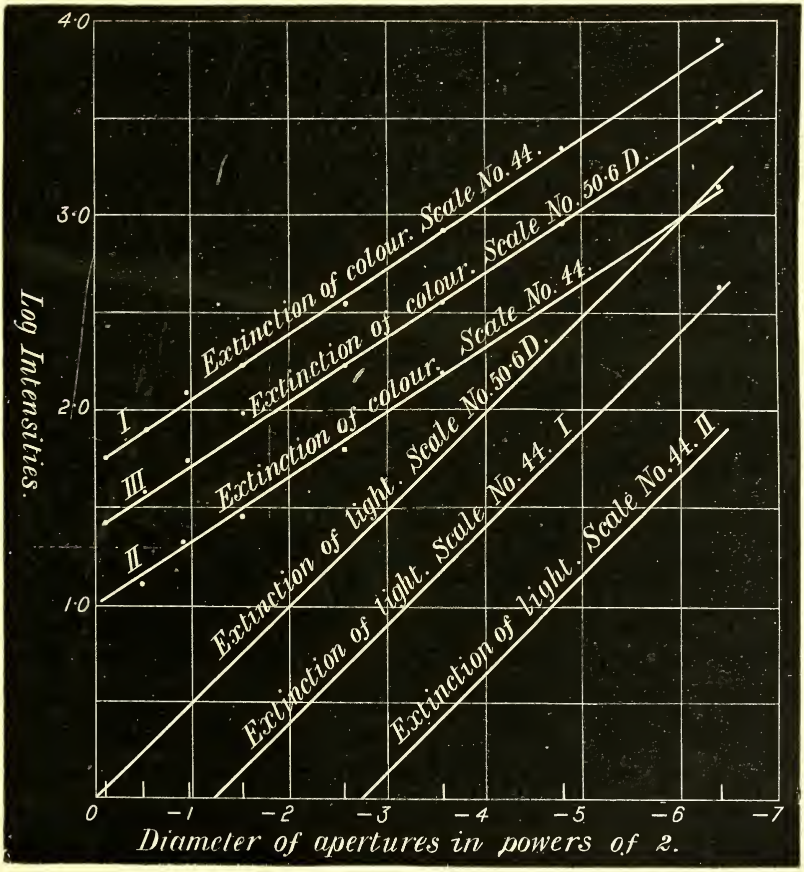


FIG. 53.

as the point at which the colour vanished. A large number of different rays were examined with the centre of the retina for colour persistency in this way, but the following will suffice to show that the colour extinction follows a definite rule as the aperture is diminished.

Nos. I. and II. are the same ray (Scale No. 44), but with different intensities to commence with. No. I. was measured by the writer, and No. II. by another observer. No. III. was read by the writer, and was D in the spectrum or Scale No. 50·6. It may be remarked that with the small apertures the extinction of colour in the red was impracticable, as the extinction of light and colour took place together, as it should do according to other experiments.

The intensity of the light to just cause a loss of colour may be *increased* tenfold when the aperture is *diminished* to one-eighth the diameter. In the extinction of light, we shall see presently that the same increase in intensity only requires a diminution to one-quarter the diameter.

This seems to show that the stimulus required to produce colour is of a different order from that required to produce light.

The Extinction of Light for the different parts of the Spectrum.

The next problem relating to this part of the subject is the measurement of the reduction in intensity of radiation, in order not only to extinguish colour, but also to extinguish any sensation of light. In these observations, the greatest care must be taken to obtain the most sensitive condition of the retina. It is useless to attempt any serious readings until the eye has been in

darkness for at least twelve minutes, if it has been previously saturated with ordinary daylight. The following table shows readings made by the writer in extinguishing light after the eye had been immediately withdrawn from the daylight of the laboratory. The increase in sensitiveness seems to follow a hyperbolic curve where the times of reading are the abscissæ and the ordinates the extinction reading.[1]

TABLE XVI.

Times of Observation.	Readings.
At the commencement	1
After 38″	3·2
,, 53″	4·9
,, 1′ 11″	6·9
,, 1′ 44″	10·5
,, 2′ 43″	17
,, 3′ 44″	27·5
,, 4′ 52″	43
,, 5′ 59″	63
,, 6′ 41″	78
,, 7′ 28″	89
,, 8′ 32″	96
,, 10′ 46″	103
,, 12′	103

The extinctions are the reciprocals of the readings.

It is obvious that the best theoretical plan of making observations would be to cut off all the light, and then gradually add small intensities little by little until the sensation of light was felt. By this procedure the eye remains in its most sensitive condition. Practically, this plan does not commend itself for adoption entirely.

[1] It must be remarked that in all these researches the time occupied in darkness was frequently more than two hours. The readings of the extinction of light of the spectrum were repeated two or three times, and the only light that reached the retina was that of the very feebly lighted spot which had to be extinguished.

It is found that when extinctions have to be made, the eye should see a *very faint* glimmer of light, which gradually has to be reduced till the sensation of light has gone. The eye becomes very difficult to control as to the direction of its axis when there is nothing which can fix it. When a search has to be made for the advent of the first small glimmer, it very often occurs that the reading is rendered useless from the fact that the eye has wandered during the observation. If the light is kept feeble in the first instance, the sensitiveness of the retina is not sensibly impaired, and concordant readings can be readily obtained.

Extinction is occasionally rendered difficult from "intrinsic" light in the eye, even when it has been kept a long time in the darkness. Sometimes there will appear to be a flash of light exciting the whole of the retina, such as may be felt when pressing the eyeballs. Whether these flashes are due to blood pressure or some other cause, it is not for a physicist to say. They are absent apparently when the health of the observer is good and the mind at rest. This intrinsic light has to be discounted, but when a number of series of observations have been made, the observer will soon know whether he is observing a flash, or whether he is making a true observation of extinction.

The original apparatus the writer employed was usually of the form described below, but variations in its arrangement and in the methods of observations were made from time to time, in order to track out any possible source of error.

BB (Fig. 54) is a closed box 3 ft. long and about 1 ft. wide and 1 ft. high, having two circular apertures $1\frac{1}{2}$ in. in diameter in the positions shown. The aperture at the side is covered on the inside by a piece

of glass, *a*, finely ground on both sides, and a tube, T, is inserted in which diaphragms, D, of any required aperture can be inserted. E is a tube fixed into the other aperture, and should for comfort be fitted with an end shaped to receive the eye, as the observations are made through it. S is a cardboard screen inserted from

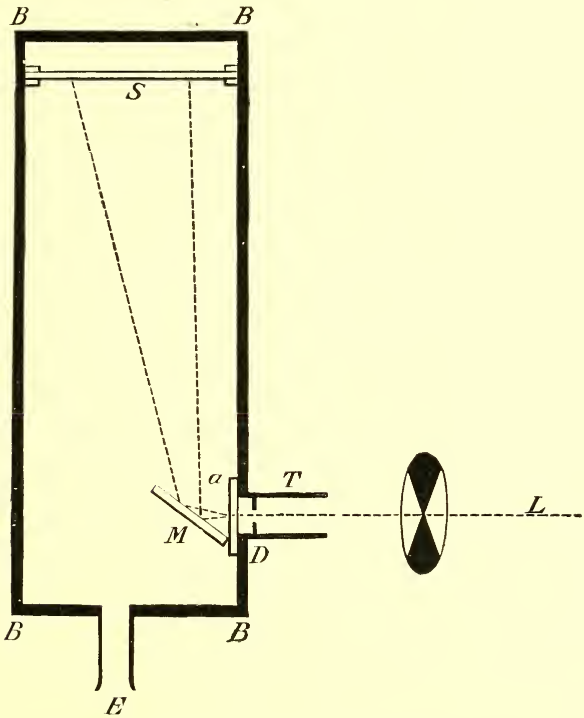


FIG. 54.—Apparatus to Measure Extinction of Light.

the top of the box, the aperture being rendered light-tight by a batten. The screen is black except one circular patch, which can be altered at pleasure in colour or size, but which in the experiments now to be described was white and $\frac{3}{4}$ in. in diameter.

When using this instrument the beam to be ex-

tinguished was directed through the tube T and diaphragm D on to a doubly-ground glass by which it was diffused. A portion of the diffused beam was reflected by the mirror M to the white patch on the screen at S. By altering the diaphragm D, the amount of light falling on S can be varied at pleasure, and it can be still further regulated by putting the rotating sectors in the path of the incident beam outside T.

The point of extinction was observed as follows. The slits of the collimator and of the slide were closed to convenient widths, and the light was subsequently diminished by inserting diaphragms. Two methods of extinction were tried: (1) The slit traversing the spectrum was moved until the ray was found which was just extinguished with each diaphragm; and (2) after placing the slit in fixed positions in the spectrum at a known ray the light was diminished by the rotating sectors as well as by the diaphragms. The latter is evidently the more convenient plan, but both were fully tried in order to determine whether the method of reducing the light by the rotating sectors could be relied on in experiments of this nature. The agreement between the results obtained, which was as close as could be expected in such experiments, convinced us of the trustworthiness of the latter method.

The diaphragms used at D admitted the following proportions of the original light to the screen S.

No. 0, $\frac{1}{90}$; No. 1, $\frac{1}{155}$; No. 2, $\frac{1}{208}$; No. 3, $\frac{1}{270}$; No. 4, $\frac{1}{478}$; No. 5, $\frac{1}{620}$; No. 6, $\frac{1}{956}$; No. 7, $\frac{1}{2430}$.

The method of diminishing the illumination of the screen by ground glass was found to be most effective. A beam of monochromatic light from the brightest part of the spectrum can be diminished to such an extent as to come within the limits of extinction by the rotating

sectors, with the apertures of such an angular dimension as to be properly read (say, more than 6°).

The D light coming through the spectrum slit was measured against an amyl lamp (or candle) by placing a white opaque screen at the aperture *a* (the tube T being removed). The luminosity of the D light being thus known, that of any other ray could be calculated from the curve A in Fig. 32. Another method of observation was as follows. A diaphragm with a small circular aperture was placed in front of the last prism of the

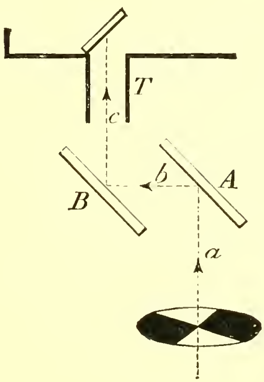


FIG. 55.—Method of Double Reflection into Extinction Box.

colour patch apparatus. The patch of light on the screen was now a small circular disc, instead of being square, as before. A similar box was prepared to that of Fig. 54, but the ground glass was omitted. The ray of light now falling on M formed a circular patch on the screen S, but the beam of light so formed is too powerful to be extinguished by any readable aperture of the rotating sectors; it was therefore further reduced by placing in its path, and at an angle of 45° to it, two parallel mirrors A, B (see Fig. 55). Each mirror can be either silvered or plain glass; three com-

binations of different reducing powers are therefore possible, viz.: (a) both mirrors silvered; (b) one plain and one silvered; (c) both plain.

The proportion of the light reflected with each combination can be readily determined. When the last was used, the intensity of c was almost exactly $\frac{1}{100}$ of that of a. As the rotating sectors gave a further extreme reduction of, say, $\frac{1}{15}$, a could be used of a manageable intensity.

When employing this method, the collecting lens in front of the spectrum was so adjusted that the recombined beam from the whole spectrum formed a circular spot on S, the position of the spot of light on S was therefore the same for all parts of the spectrum.

The absolute luminosity of the beam from D of the spectrum was measured by placing an open screen at the same distance from the mirror M (Fig. 54) that S was, two silvered mirrors being used at A and B, and using the amyl-acetate lamp for comparison. The absolute luminosities of beams from other parts of the spectrum were then calculated from this by means of the luminosity curves.

The results obtained by using the rotating sectors with this apparatus were also tested by the method before described, and were found to be perfectly trustworthy.

From the observations made a curve was plotted showing what was the proportion of the beam from each part of the spectrum which was just not visible. The absolute luminosity of each part of the spectrum having been determined in the way explained above, a second curve was plotted, of which the ordinates represent the absolute luminosity of each part of the spectrum at the extinction point, or, in other words,

the proportion which would be just not visible, supposing that each part had been originally of the uniform luminosity of, say, one candle. This curve rose from the blue-green towards the red, when, after reaching a maximum, it tended to drop again. There appeared to be a similar irregularity at the violet end. It was suspected that these irregularities might be caused by some admixture of white light due to want of perfect transparency of the prisms, and further investigation showed that this was possibly the case, and that when this stray white light was eliminated the curve became of the form shown by the dotted line, Fig. 56.

A combination of "cobalt blue" and a "blue-green" glass was used for the violet end of the spectrum, and "stained-red" glass—*i.e.* glass flashed on one side with copper, and on the other with gold—for the red end.

The luminosity of each beam after passing through the medium was determined, also the proportion left when it was reduced so as just to extinguish the light, the product of the numbers representing these quantities would evidently represent the absolute luminosity at the point of extinction, or, in other words, the proportion left on the supposition of a uniform luminosity for all parts of the spectrum.

The next figure shows the results of the extinction of light in the different parts of the spectrum by an eye neither myopic nor astigmatic, and which had normal colour vision.

To the left of E there are two branches to the curve; the one shows the extinction when the central part of the retina is used, and the other when the whole eye is allowed to wander over the end of the box. As there is no absorption by the yellow spot in these last,

they show that a greater diminution of the light is required than after the rays pass through the absorbing

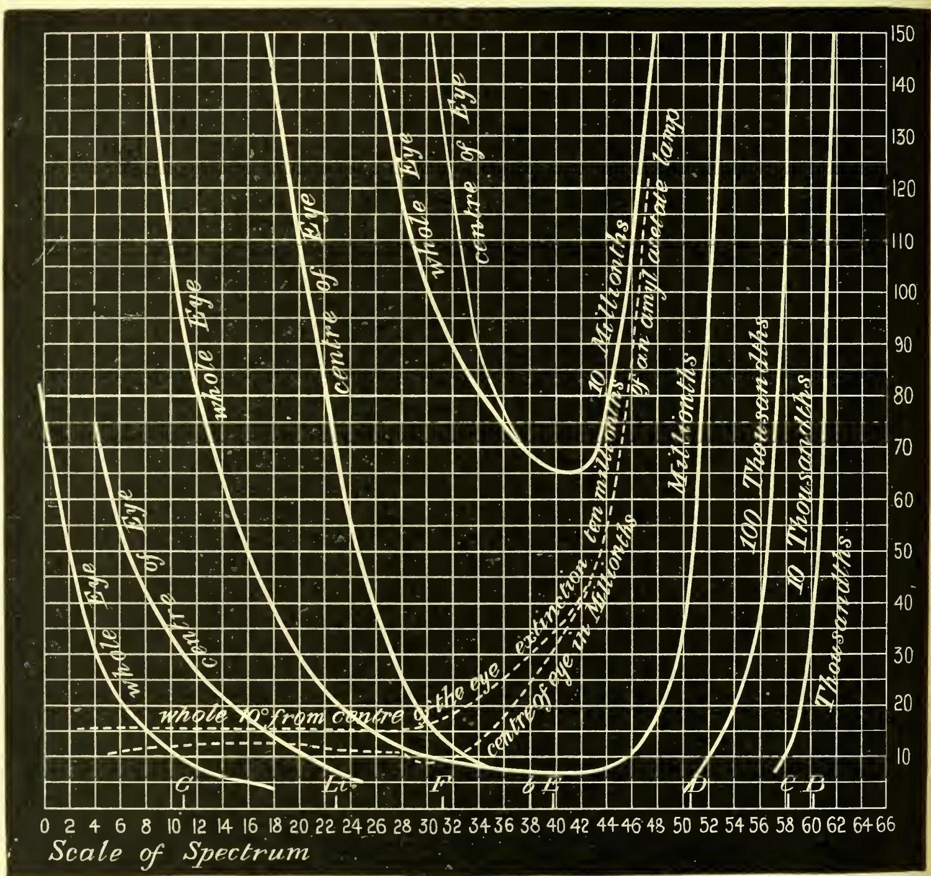


FIG. 56.—Extinction Curves of Normal Eye.

The continuous line curves show the proportion of the beam from each part of the spectrum which is just not visible, the illumination by the beam from D when unreduced being equal to that of one amyl-acetate lamp at 1 ft. from a screen.

The dotted curves show the proportion, supposing that all beams had equal intensity to that of D.

medium. The tables give the measures of each for reference.

TABLE XVII.—*Extinction by Central Portion of Normal Eye.*

I.	II.	III.	IV.	V.	VI.
Scale No.	Wave-length.	E. Reduction of original luminosity in millionths to cause extinction.	L. Luminosity of original beam.	$\frac{E \times L}{100}$.	Persistency curve $\frac{650}{E}$ (Maximum = 100).
62	7957	15,000	2	300	...
60	6728	3,750	7	262·5	...
58	6520	1,050	21	220·5	·62
56	6330	380	50	190	1·71
54	6152	196	80	156	3·32
52	5996	97	96	93·12	6·7
50	5850	35	100	35	18·6
48	5720	17	97	16·49	38·2
46	5596	10·2	87	8·87	63·7
44	5481	7·4	75	5·55	87·8
42	5373	6·55	62·5	4·09	99·5
40	5270	6·55	50	3·27	98·5
38	5172	6·85	36	2·46	95
36	5085	7·6	24	1·82	81·3
34	5002	8·8	14·2	1·25	74
32	4924	11·6	8·5	·988	56
30	4848	16·3	5·5	·896	40
28	4776	26	4	1·04	25
26	4707	38·5	2·8	1·078	16·9
24	4639	56	1·82	1·019	11·6
22	4578	80	1·4	1·12	8·41
20	4517	107	1·08	1·156	6·1
18	4459	140	·86	1·204	4·64
16	4404	180	·7	1·26	3·6
14	4349	220	·56	1·232	2·95
12	4296	270	·45	1·215	2·4
10	4245	335	·34	1·139	1·94
8	4197	430	·26	1·118	1·51
6	4151	510	·18	·918	1·27
4	4106	750	·14	1·05	·86

TABLE XVIII.—*Extinction by Whole Eye.*

I.	II.	III.	IV.	V.	VI.
Scale No.	Wave-length.	E. Reduction of original luminosity in millionths to cause extinction	L. Luminosity of original beam.	$\frac{E \times L}{160}$.	Persistency curve $\frac{650}{E}$ (Maximum = 100).
38	5172	6·9	41·5	2·86	94·2
36	5085	7·4	33·5	2·48	87·8
34	5002	8	26·5	2·12	81·2
32	4924	8·8	21	1·85	73·8
30	4848	10	16·5	1·65	65
28	4776	11·5	13	1·49	56·5
26	4707	14·5	10·5	1·52	44·8
24	4639	18·5	8·2	1·52	34·1
22	4578	23	6·3	1·45	28·3
20	4517	30	5	1·5	21·7
18	4459	39	4	1·56	16·7
16	4404	51	3·1	1·59	12·3
14	4349	66	2·3	1·52	9·85
12	4296	80	1·9	1·52	8·12
10	4245	110	1·4	1·54	5·91
8	4197	154	1	1·54	4·22
6	4151	204	·75	1·54	3·18
4	4106	307	·5	1·54	2·11
2	4063	513	·3	1·54	1·26
0	4020	770	·2	1·54	·84

Column VI. in this and the previous table requires a little explanation. It is called the persistency curve,[1] and is derived from the *reciprocals* of the original extinctions, making the maximum 100. A little consideration will show that this curve is the luminosity curve of the spectrum at the point of extinction. A comparison of this curve with the luminosity curve of a feeble

[1] General Festing and the writer gave it this name, though it has been given by others to a different curve.

spectrum will show that the two are identical when the maxima are made equal. We shall have to revert to this curve in a subsequent chapter.

Modified Extinction Box.—In later experiments made to test the effect the size of the spot had on the extinction, a new form of extinction box was designed, which for some purposes is more convenient than that already described, since a graduated annulus, instead of a sector, can be used with it.

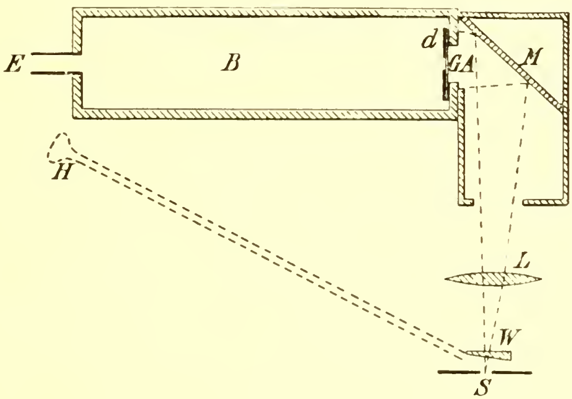


Fig. 57.

At the end of the box, B, an aperture was cut, which was closed by a piece of glass, G, finely ground on each side, or by an opal glass. Provision was made for the insertion of diaphragms, *d*, in front of the glass. The eye-tube, E, was at the opposite end of the box, as shown. Outside the box was a mirror, M, enclosed in a frame, as indicated. The slit, S, in the spectrum and the collecting lens, L, together with the annulus, W, are shown in the figure. H is the handle used to move the annulus round its axis. This form of box only admits light through the end ; there is no reflected light in the inside. The one thing necessary is to secure a good

scattering of light by the ground or opal glass, so that the direct light is inappreciable compared with that scattered, a desideratum which is obtained by using one or two glasses ground on each surface. The box in which M is fixed is blackened, or lined with black velvet, and M itself can be either silvered or plain glass. In the old arrangement the light entered from the side and by reflection, and, after passage through ground glass, illuminated a white disc at the end of the box. When the disc was of fair size, any reflections from the black interior were extinguished long before the light from the disc itself vanished, and hence no inconvenience was felt from the presence of the light from the black interior, which may be taken as about $\frac{1}{30}$ of that reflected from the disc. If, however, the area of the white disc is very much diminished, the illumination, as will be seen presently, may be as much as 100 times greater than on the larger disc and yet be invisible, and then the reflection from the interior of the box would be visible after the extinction of light on the small disc was completed. For this reason the new form of extinction box was designed.

The first object in view was to ascertain whether there is any difference in the extinction values of large and small areas of light—that is, whether the images on the retina are more speedily lost when the angles they subtend are small than when large, and, if so, whether the extinction of each separate spectrum colour remains in the same proportion. For example, whether the reduction in light necessary to produce extinction of a 2-in. disc of colour at G, Fig. 56, is the same for a disc of $\frac{1}{2}$ in. or $\frac{1}{4}$ in. (the angular measures of these when the apparatus described above is employed are $4° \ 11'$, $1° \ 3'$, and $31'$), and, if not,

whether the reductions for every colour are proportional. A series of observations made with these and other discs showed that the smaller the disc the less reduction in intensity of the ray was required to extinguish it, and that the same ratio existed between the extinction of the different colours. Fig. 58 shows graphically the results, which are in logs. of the extinction value instead of the natural numbers. [This enables the diagram to give the various curves without having to change the scale value of the ordinates, as was the case in the last diagram.]

There are five curves shown in all. No. I. is the 2-in. disc, No. II. the ·5-in. disc, No. III. the ·25-in. disc. No. V. is the curve at p. 165 reduced to log. ordinates. No. IV. is a pin-hole disc subtending an angle of 1′ 29″. All these curves within the limits of error of observation are parallel to one another, and as the ordinates are logarithms this indicates that the rays are extinguished proportionally. For curves I., II., and III. the D light thrown on the ground glass, G, was ·17 of an amyl acetate (AL.) standard light at 1 ft. distance (which is very closely ·17 of a candle). With curve V., to which reference has already been made, the D light was 1 AL. at 1 ft. distance. If the correction be made for this difference of initial illumination, curve V. would lie on curve I. With curve IV., where the disc had a diameter of ·012 in. and an angular aperture of 1′ 29″, the light had to be increased very largely to enable any readings to be taken. It is inserted here to show that with this small disc the curve is still parallel to the others. To obtain the diagram, the original readings were plotted[1] and free-hand curves

[1] For original readings, see Paper No. 7.

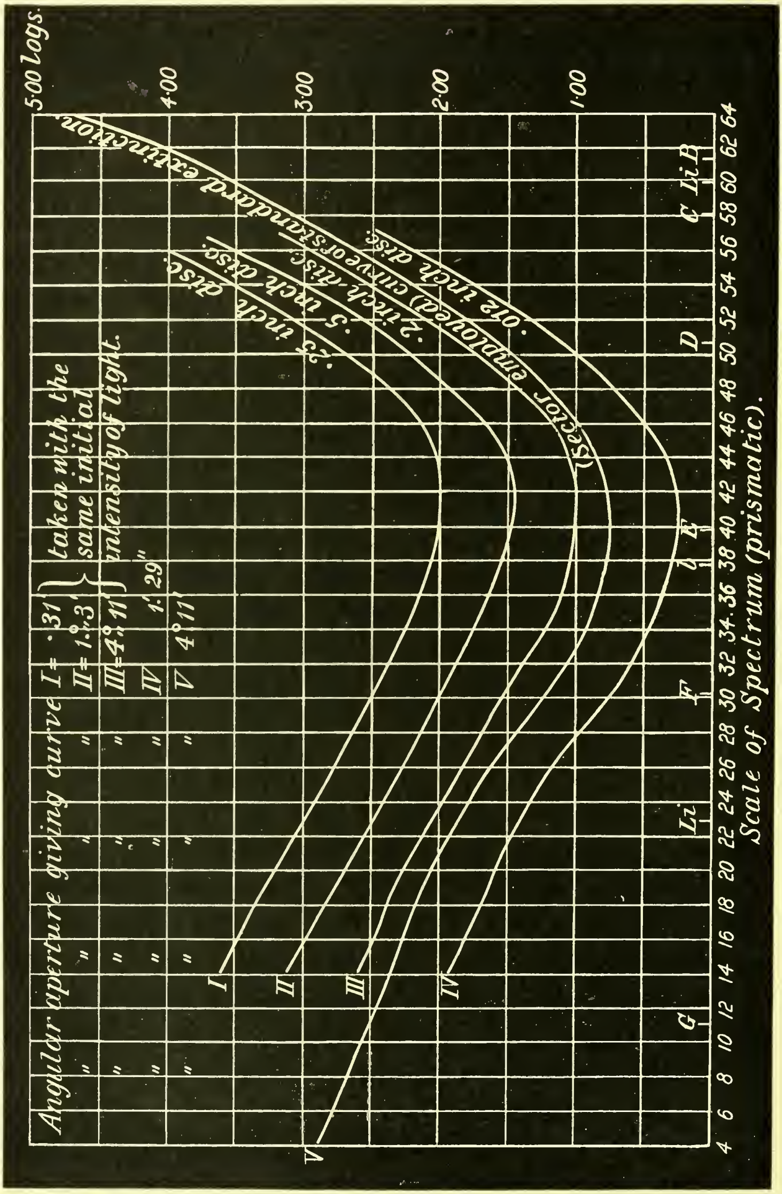

Angular aperture giving curve I = ·31′
" " II = 1°3′
" " III = 4°11′
" " IV 1°29″
" " V 4°11′
taken with the same initial intensity of light.
5·00 Logs.
4·00
3·00
2·00
1·00
(Sector employed) curve of standard extinction.
·012 inch disc.
·2 inch disc.
·5 inch disc.
·25 inch disc.
I
II
III
IV
V
G
Li
F
b
E
D
C
Li
B
4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64
Scale of Spectrum (prismatic).

Fig. 58.

drawn through them. The curves were made from the following readings :—

TABLE XIX.

Scale Nos.	λ.	Standard curve. Curve V.	2-inch disc. Curve I.	½-inch disc. Curve II.	¼-inch disc. Curve III.
60	6728	3·6	...	...	...
58	6520	3·07	...	...	...
56	6330	2·6	2·85	3·42	3·9
54	6152	2·2	2·4	2·95	3·4
52	5996	1·87	2·05	2·55	3·03
50	5850	1·54	1·75	2·2	2·72
48	5720	1·25	1·45	1·95	2·42
46	5596	1·02	1·25	1·75	2·25
44	5481	·87	1·1	1·57	2·09
42	5373	·82	1·05	1·52	2·02
40	5270	·82	1·05	1·52	2·03
38	5172	·84	1·07	1·57	2·07
36	5085	·88	1·1	1·6	2·1
34	5002	·95	1·2	1·7	2·2
32	4924	1·07	1·35	1·83	2·35
30	4848	1·22	1·55	1·97	2·5
28	4776	1·41	1·62	2·12	2·62
26	4707	1·58	1·82	2·35	2·82
24	4634	1·75	2·02	2·52	2·97
22	4578	1·91	2·15	2·65	3·07
20	4517	2·05	2·28	2·77	3·2
18	4459	2·14	2·35	2·9	3·32
16	4404	2·25	2·5	3	3·47
14	4349	2·34	2·57	3·15	3·58
12	4296	2·43	...	...	...
10	4245	2·52	...	...	...
8	4197	2·63	...	...	...
6	4151	2·75	...	...	...
4	4106	2·87	...	...	...

It has already been mentioned that some eyes have a larger amount of colouring matter in the yellow spot than others. The following table shows the difference between the extinction of such an eye and one possessing an ordinary amount of pigmentation. The light used in this case was the arc light with the horizontal positive carbons. The D light was 1 candle at 1 foot in each case. The luminosities of the ray, multiplied by the

absolute extinction value, were practically the same in each case, as would be expected.

SSN.	Pigmentation.		SSN.	Pigmentation.	
	Normal.	Excessive.		Normal.	Excessive.
	Log.	Log.		Log.	Log.
60	3·64	3·65	30	·98	1·09
58	3·03	3	28	1·07	1·25
56	2·53	2·55	26	1·27	1·43
54	2·06	2·17	24	1·35	1·57
52	1·77	1·8	22	1·5	1·74
50	1·47	1·5	20	1·63	1·91
48	1·22	1·27	18	1·78	2·05
46	1·01	1·02	16	1·92	2·27
44	·87	·87	14	2·06	2·5
42	·83	·82	12	2·26	2·82
40	·82	·82	10	2·42	3
38	·87	·85	8	2·59	3·25
36	·88	·86	6	2·81	3·42
34	·89	·88	4	3	3·65
32	·92	·95			

Law Connecting the Angular Aperture with the Extinction.

The next investigation carried out was to ascertain if any law connected the angular aperture of the object observed with the diminution of the intensity of the light which was required to cause invisibility. For the purpose, a large number of diaphragms of very differing apertures were inserted in front of the ground glass (Fig. 57). For the sake of plotting, in the first instance, and as they give the most rational scale, the diameters of the discs were expressed in powers of 2, thus $\frac{1}{2}$ inch, which is 2^{-1}, is used on the scale of abscissæ as -1; $\frac{1}{4}$ as -2, and so on—all diameters not being expressed in exact powers of 2 being calculated out in the ordinary way.

TABLE XX.—*The following are the values, in inches, of the apertures used. The table also gives the angles subtended and the values in powers of* 2.

Diameter in Inches.	Angles Subtended.	Value in Powers of 2.
2	4° 11′ 0″	+1
1·5	3° 8′ 0″	+ ·6
·94	1° 57′ 0″	− ·09
·725	1° 30′ 0″	− ·48
·525	1° 5′ 0″	− ·93
·42	0° 52′ 35″	−1·25
·35	0° 43′ 43″	−1·52
·3	0° 37′ 33″	−1·74
·17	0° 21′ 17″	−2·56
·086	0° 10′ 46″	−3·56
·036	0° 4′ 30″	−4·81
·012	0° 1′ 30″	−6·4

These diaphragms were placed in front of the ground glass, and the light from the discs thus formed extinguished. In the first set of experiments, the pure colours of the spectrum were employed; whilst in the others, ordinary lamp light and lamp light screened with different colour glasses or solutions were used, and identical results were found in all cases. The following figure (Fig. 59) was made from the mean readings of some of the different series.

(The dotted line in the bottom curve was obtained by calculation from the top curve.)

The indications here given are that the curves with apertures less than 1½ in. diameter become straight lines, all of which are parallel, and it is somewhat remarkable that from that point the intensity of a light which will be just extinguished with a certain diameter of aperture may be increased ten times, and yet be invisible when an aperture with one-quarter of that diameter is employed; if the intensity of the light be

increased 100 times, we have only to diminish the diameter of the aperture to one-sixteenth, and it will again disappear, or if to one-sixty-fourth, the light may be increased 1000 times. There must, of course, be some

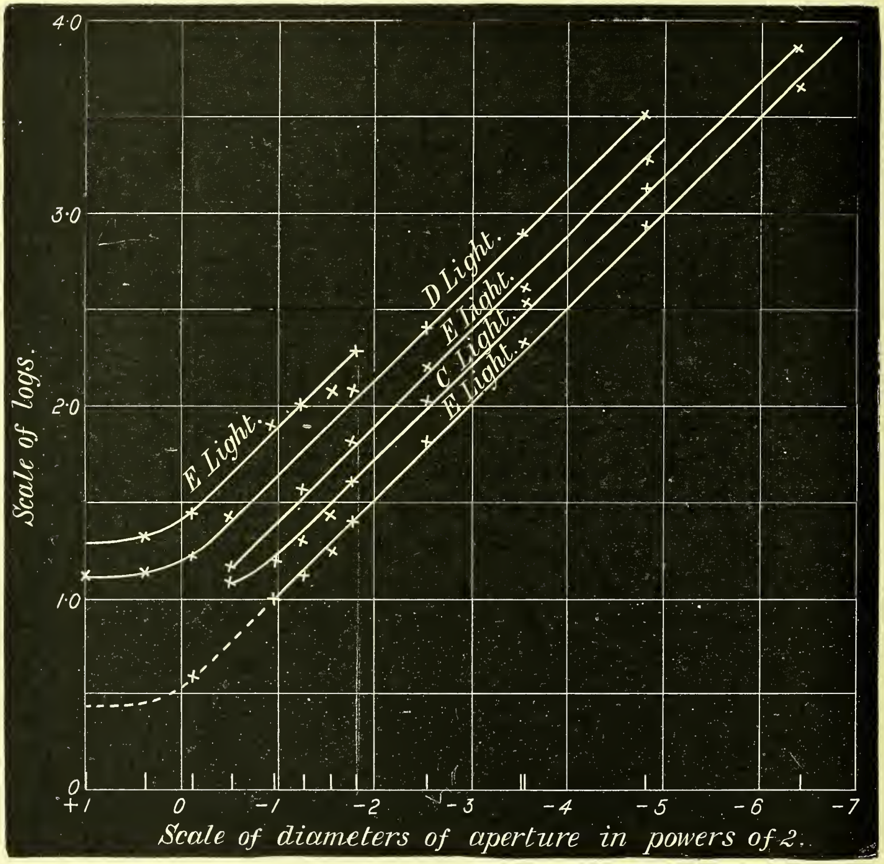


Fig. 59.

lower limit to this when the image, that of the small disc of light, which a point such as a star subtends in the retina. When the angular aperture exceeds 4°, apparently the upper limit is reached, all extinctions being the same beyond it.

Extinction dependent on the Least Diameter of the Aperture.

In making extinctions of light, the observer must be struck with the fact that before it finally disappears the

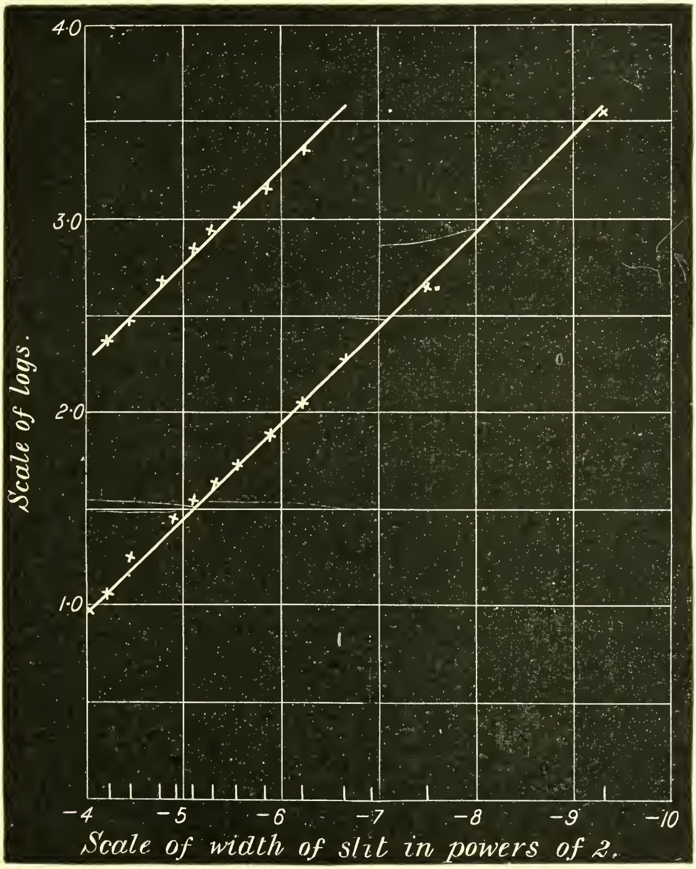


FIG. 60.

shape of the disc or object entirely disappears, and that an irregularly-shaped spot is formed before it vanishes. This phenomenon naturally leads to the query as to whether within limits the shape of the illuminated spot has any effect on the extinction. One of the earliest

experiments gave at all events a partial answer to the query. A slit was placed against the ground glass in the apparatus (Fig. 57), and the extinction made with lines of light varying between ·0015 to ·06555 in. in width, so that the widest aperture was about forty times broader than the narrowest, the length of the slit being the same in all. The slit was illuminated with white light or coloured light in the experiments made. The extinction values were plotted diagrammatically, the abscissæ being the *widths* in powers of 2, and the ordinates the logs of the intensities of radiation, just invisible as before. Fig. 60 shows the results with white light and red light.

The top slanting line is the extinction of a red light and the lower one a white. The observations show that for every diminution in width to one-quarter, the extinction value of the light may be increased ten times.

The table below shows the widths of the slits in powers of 2, and the annulus readings converted into logs.

TABLE XXI.

White Light.				Red Light.			
Absolute Width in Inches.	Width in Powers of 2.	Readings.		Absolute Width in Inches.	Width in Powers of 2.	Readings.	
		Degs.	Logs.			Degs.	Logs.
·06155	− 4·02	350	·99	·05355	− 4·22	192	2·35
·05355	− 4·22	342	1·06	·04555	− 4·46	176	2·45
·04555	− 4·46	323	1·23	·03755	− 4·73	154	2·68
·03355	− 4·9	298	1·44	·02955	− 5·08	135	2·84
·02955	− 5·08	285	1·55	·02555	− 5·29	124	2·94
·02555	− 5·29	275	1·63	·02155	− 5·53	110	3·05
·02155	− 5·53	267	1·72	·01755	− 5·83	98	3·16
·01755	− 5·83	250	1·85	·01355	− 6·2	76	3·35
·01355	− 6·2	228	2·04	·00955	− 6·67	50	3·57
·00955	− 6·67	202	2·26				
·00555	− 7·49	156	2·67				
·00155	− 9·33	54	3·53				

Taking into consideration the extinction curve of the spectrum, and these results, we can see how the green lines of a feeble spectrum will be the first to be seen (perhaps colourless), whilst others, though present, will fail to be seen except with a very wide slit.

A further experiment was made which confirmed the previous measures. The extinction of the light from a circular, a square, and a rectangular aperture of the same area was made. The circular aperture had a diameter ·94 in., the sides of the square were ·84 in., and of the oblong 1·68 × ·42 in. In addition, an oblong aperture ·84 × ·42, exactly half the latter, was also used.

The following are the results of the extinction, and in the last column are given the results that would have been obtained from the curves already described :—

Table XXII.

Aperture.	Width in Powers of 2.	Readings.		Logs from Diagram.
		Degrees.	Logs.	
Circular disc, ·94 in. diam. .	− ·09	234	1·98	1·98
Square, ·84 in. side . . .	− ·25	216	2·14	2·15
Rectangle, 1·68 × ·42 in. . .	− 1·25	152	2·69	2·65
Rectangle, ·84 × ·42 in. . .	− 1·25	154	2·68	2·65

Remarks on this table seem unnecessary, as they so plainly indicate the guiding factor in the extinction.

This perhaps is one of the most curious results that have been obtained, for it is hard to conceive that the area of the retina impressed should not be a factor. The experiments clearly show that the estimate of small intensities of light by their effect on the light-perceiving apparatus is not a simple matter. The extinction of comparatively larger areas of light is most instructive. The light from a square, or a disc, or an oblong, just

before extinction, is a fuzzy patch of grey, and appears finally to depart almost as a point. This can scarcely account for the smallest width of an illuminated surface determining the intensity of the light just not visible; but it tells us that the light is still exercising some kind of stimulus on the visual apparatus, even when all sensation of light is gone from the outer portions. The fact that the disappearance of the image takes place in the same manner, whether viewed centrally or excentrically, tells us that this has nothing to do with the yellow spot, or fovea, but is probably due to a radiation of sensation (if it may be so called) in every direction on the retinal surface. Supposing some part of the stimulus impressed on one retinal element did radiate in all directions over the surface of the retina, the effect would be greatest in its immediate neighbourhood, and would be inappreciable at a small distance, but the influence exerted upon an adjacent element might depend not only on its distance, but also upon whether it was or was not itself excited independently. Following the matter out further, we should eventually arrive at the centre of an area, as the part which was the recipient of the greatest amount of the radiated stimuli, and consequently that would be the last to disappear. With a slit aperture, the slit is visible till extinction is very nearly executed, but it finally merges into a fuzzy spot at the moment before it finally fails to make any impression of light.

Extinction of Light received Excentrically on the Retina.

An investigation into the extinction of light at different angular distances from the centre of the eye was attempted. The experiments are of a very difficult

nature, and it requires long practice to enable a satisfactory series to be made.

The method adopted was to place a pin, with a head painted with Balmain paint, at every 5° from the central line joining the illuminated aperture and the position occupied by the eye. The paint was *very* feebly phosphorescent, and only just sufficient to fix the centre of the eye at the required angle from the object. The results of two experiments, red and white light (paraffin), at 10°, are given. It appears from these that at this angular distance the extinction of all light from the red takes place when the light is about one-third brighter than is required for the centre of the eye. With the paraffin light it is somewhat less. With green light about E, and with blue at the lithium line, the necessary reduction of the light is greater than for the centre of the eye, a result already shown.[1]

TABLE XXIII.

Aperture.	Angle.			2^{-x}	Red Light.		White Light.	
					Direct.	10° from axis.	Direct.	10° from axis.
	°	′	″					
·94	1	57	0	·09	275	255	305	290
·724	1	30	0	·48	252	230	270	265
·525	1	5	0	·93	225	204	265	240
·42	0	52	35	1·25	217	195	252	230
·35	0	43	43	1·52	195	174	235	220
·3	0	37	33	1·74	185	162	215	200
·17	0	21	17	2·56	152	125	174	157
·086	0	10	46	3·56	93	75	118	105

There is a further falling-off of sensitiveness at greater angles than those shown in the tables, but the extinction is very difficult to make with certainty.

[1] See Paper No. 4.

Extinction of Light and Colour together.

At p. 155 the result of the extinction of *colour* in connection with the angular aperture was given, and Fig. 53 shows the results diagrammatically; but it also shows the extinction of *light* for the same rays. From the diagram we can see that there is an angular aperture subtended on the retina at which any ray will be extinguished both for colour and light at the same time. The red ray is that for which the aperture will be the largest.

Luminosity of the Light coming through different Apertures.

As a side issue to extinction, the following observations were made, as having a bearing on the necessity of keeping the two patches of colour and light equal in making measurements of luminosity.

The point investigated, but without any great degree of detail, was the comparative luminosities of the same light coming through two apertures of different diameters. The method adopted was as follows. The ground glass was illuminated uniformly with the light to be tested, and two apertures cut in a black mask were placed in contact with it, as shown (Fig. 61). Sectors were placed close behind the larger aperture, and rotated with angular apertures of any desired amount. In front of the collimator of the colour patch apparatus the annulus was placed so that a regular diminution of the light could be effected. The sectors having been set at

Fig. 61.

90°, the light coming through the bigger aperture was diminished to half. *As the light coming through the small aperture is extinguished long before that coming through the larger one*, there must be some intensity of light in the extinction box when the two apertures will appear equally bright to the eye. The light coming through the slit is therefore diminished till the two appear equally bright. The diminution of light is noted, that coming through the larger aperture being diminished twice as much as that coming through the smaller. The sectors are again set at 45°, and the same procedure adopted as before. In making these determinations, the eye has to judge the brightness of very dissimilar sizes of area, and it might be thought that this fact would present an almost insuperable difficulty in making very accurate measures. As a matter of fact, it was not so; the greatest difficulty was encountered in those cases when the light of the large aperture was so diminished that it became colourless, whilst the other had very nearly its original tint. The red was perhaps the hardest to judge on that account; the other colours did not present any great difficulty. One of the curious phenomena encountered in these measures at times was a distinct scintillation of the light emitted by the small aperture. Sometimes this was perplexing, but never to the extent to render the comparisons uncertain.

Fig. 62 shows the results when the two circular apertures are ·94 in. and ·086 in. in diameter. The top slanting line is where the illumination was by a blue ray of the spectrum (SSN. 27·3), and the lower the D sodium or SSN. 50·6.

What are usually abscissæ are the log readings given by the annulus, together with the sector readings (converted into annulus readings), which rotates behind the

large aperture, and the ordinates are the logs given by the annulus alone. The luminosity of the large spot is equal to that of the small spot under these conditions. If the luminosity of the spots were always equal, no matter what size they were, the sector would have to be at 180, *i.e.* not rotating, and the inclination

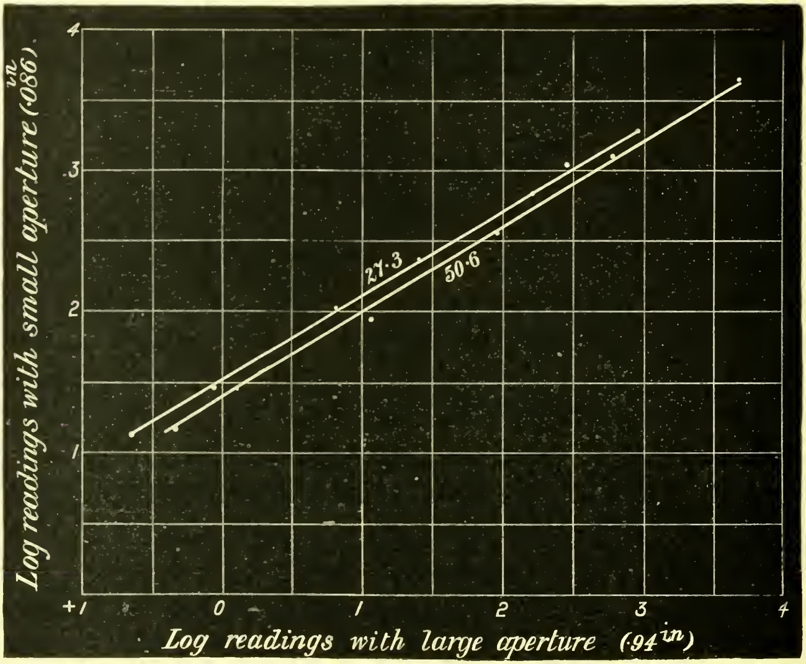


Fig. 62.

of the slanting lines would be 45°. As the sector is, however, required, the inclination is less than 45°, as shown in the figure, and this gives a value of the intensity of the light at each spot when to the eye the luminosity is the same. The slanting lines are straight, and the inclination is alternatively determined by the extinction values of the two apertures.

Table XXIV.

Sector in Degrees.	Equivalent Values of Annulus.	Scale No. 27·3.				Scale No. 50·6.			
		Readings in terms of Annulus Scale.		Readings converted into Logs.		Readings in terms of Annulus Scale.		Readings converted into Logs.	
		S.	L.	S.	L.	S.	L.	S.	L.
180	0	...	...	...	...	40	40	3·66	3·66
90	35	90	125	3·23	2·92	110	145	3·05	2·75
45	70	140	210	2·8	2·19	170	240	2·54	1·94
22·5	105	200	305	2·28	1·38	240	345	1·94	1·03
11·25	140	230	370	2·02	·82	300	440	1·42	·22
5·6	175	295	470	1·46	− ·04	330	505	1·16	− ·34
Extinction	200	325	525	1·21	− ·51	340	540	1·08	− ·64

S. and L. refer to the small and large apertures respectively. From Fig. 62 it is found that the extinction value of the large aperture, ·94 diameter, requires 200° more of the annulus to extinguish it than the smaller aperture ·086 diameter. This accounts for the last line in the table.

Extinction of the Light in Spectrum Colours when the Eye is not "dark" adapted.[1]

So far the experiments as to the extinction of any sensation of light were made with a retina "dark" adapted, in which condition it is most sensitive. A large number of experiments (not yet completely published) have been made by the writer and others in his laboratory on the extinction of the sensation of light when the retina as a whole is subjected to illumination by white or coloured light. For this a modification of

[1] See Paper No. 27.

the extinction box was made, and so far as the experiments themselves are concerned they may be accepted as trustworthy. There is one factor, however, which has not been taken into account, viz. the aperture of the pupil of the eye. A difference in aperture will make some difference in the amount of radiation of any ray which is just too feeble to be recognised as light.

Box used in the Extinction of Light.

B is the box, as in Fig. 63. At the end of the box is cut a hole $\frac{3}{4}$ in. in diameter, and against it, inside, is

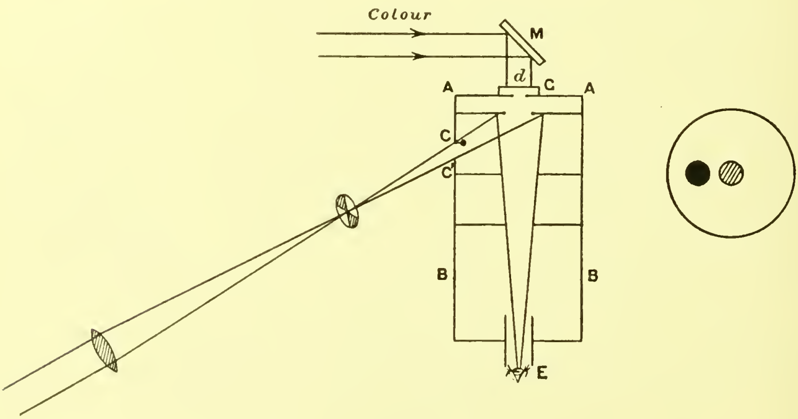


FIG. 63.

placed a 4-in. disc of white matt paper, in the centre of which is cut $\frac{1}{2}$-in. hole. Behind the box, a second end, separated from the first by an interval of a couple of inches; opposite the aperture at the end of the box, is cut another circular aperture 1 in. in diameter, against which is placed a piece of doubly-ground white glass, and a second piece can be placed behind this. The coloured

ray of the spectrum will form a patch on the ground glasses, and the aperture in the end will allow the rays to pass and be viewed through the eyepiece E, but it will be limited to the $\frac{1}{2}$-in. aperture cut out of the card. The 4-in. disc is illuminated from the reflected beam or other light through an aperture, CC, cut in the side of the box. Diaphragms are placed in the box to limit the view to the disc. At the side of CC is placed a small disc which throws a black shadow $\frac{1}{2}$ in. in diameter on the large white disc. This is taken as a measure of the blackness to be matched when extinguishing the colour. An annulus or sector is placed in the white beam, so that the luminosity may be reduced to any required extent. Another "annulus" is placed in front of the ray issuing from the slit in the spectrum. The white beam which passes through the aperture at the near end of the box falls on a dead black surface away from the aperture filled by the ground glass. The whole box is dead black. Such is the instrument which has been used, and has been found effective for the purpose.

By closing CC the value of the extinction by a dark-adapted eye can be carried out. The box is furnished with a dark hood, so that the only light that reaches the eye is from the end of the box. The shadow thrown by the small disc at C will always be of the same darkness, whatever intensity of light thrown on the white disc may be, when all the 4-in. disc is covered up except a white disc a little smaller than the shadow cast.

It is not intended to give descriptions of anything except the disappearance of the light coming through *d* and its match with the black shadow, which of course to the eye varies in blackness according to the intensity of the illumination of the 4-in. disc.

Example of an Extinction with the Retina illuminated.

In one case the luminosity of the white disc was ·2 candle after passing through an annulus at 20° of the scale. Each 25° gave exactly ½ the illumination. Measures were taken with the light passing through the annulus at 20°, 70°, 120°, 170°, and 220°, the extinction of light being made by another annulus in which every degree corresponded to ·0086 in logs.

The illuminations are for 20° . . ·2 candle.
,, ,, 70° . . ·05 candle.
,, ,, 120° . . ·0125 candle.
,, ,, 170° . . ·00312 candle.
,, ,, 220° . . ·00078 candle.

TABLE XXV.—*Table showing Comparative Extinction of the Sensation of Light when the Retina is stimulated with different degrees of White Light.*

SSN.	λ.	220°.		170°.		120°.		70°.		20°.	
		Log.	Intensity.	Log.	Intensity.	Log.	Intensity.	Log.	Intensity.	Log.	Intensity.
60	6728	2·79	624	2·9	800	3	1000	3·05	1120	3·18	1,620
58	6520	2·25	178	2·36	230	2·49	310	2·71	513	2·88	760
56	6333	1·98	93	2·02	105	2·26	182	2·45	282	2·67	468
54	6152	1·68	48	1·85	71	2·11	129	2·36	230	2·54	347
52	5996	1·46	29	1·72	53	2	100	2·32	209	2·49	309
50	5850	1·26	18	1·63	43	1·94	87	2·28	190	2·49	309
48	5720	1·16	14·5	1·55	35·5	1·89	78	2·24	174	2·54	347
46	5596	1·07	35·5	1·46	28·8	1·85	71	2·28	190	2·67	468
44	5481	1·03	10·7	1·44	27·6	1·85	71	2·32	209	2·82	660
42	5373	·99	9·8	1·46	28·8	1·94	87	2·42	263	2·92	835
40	5270	·99	9·8	1·51	32·5	2·02	105	2·58	380	3·08	1,200
38	5172	1·03	10·7	1·59	39	2·11	129	2·71	513	3·18	1,520
36	5085	1·12	13·2	1·68	48	2·21	162	2·81	640	3·31	2,040
34	5002	1·23	17	1·8	63	2·36	230	2·92	835	3·44	2,750
32	4924	1·38	24	1·89	78	2·47	295	3·06	1150	3·59	3,900
30	4848	1·46	29	2·02	105	2·58	380	3·18	1520	3·74	5,500
28	4776	1·55	35·5	2·11	129	2·69	460	3·3	2000	3·89	7,800
26	4707	1·63	43	2·21	162	2·79	620	3·35	2460	4	10,000
24	4639	1·72	53	2·31	304	2·88	760	3·48	3020	4·08	12,000

The intensities of the light in this table have to be multiplied by 7·7 to compare it with the extinction with the centre of the eye shown in Table XVII., where the scale is in millionths, and the D light is equal to 1 candle.

It will be noticed that at SSN. 60 the red ray, when the retinal illumination is ·2 candle, is extinguished

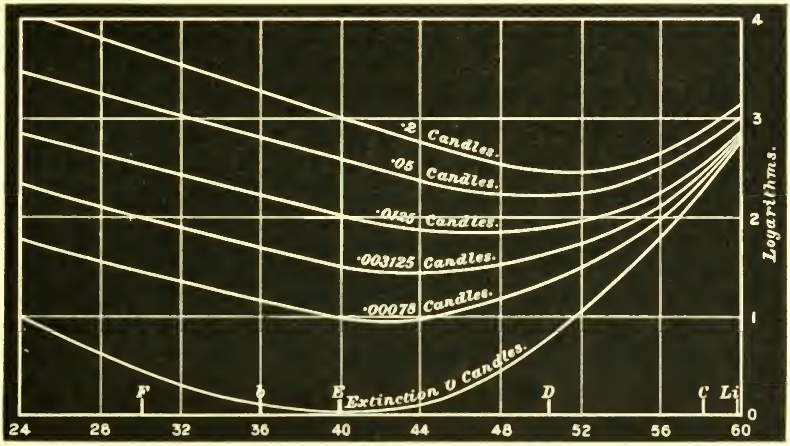


FIG. 64.

with an intensity 2·6 times greater than when the illumination is ·00078 candle, and that the ratio of the maximum extinctions are for those illuminations as 9·8 to 309, or as 1 to 32. The observation recorded on p. 148 as to the reappearance of the red when extinguishing its colour is explained by these measures. The white illuminates the retina more or less strongly, and the red colour becomes visible.

An interesting and perhaps important fact is brought out by these experiments. They show that as the white which illuminates the retina is increased, the point of

maximum extinction travels between SSN. 40 and SSN. 52. With a very strongly stimulated retina, the point of maximum extinction may lie nearer the red than the latter SSN. To illustrate this the persistency curves (reciprocals of the extinction curves) have been calculated, making the maximum in each case 100. The position of these maxima give the position of the maximum extinction.

TABLE XXVI.—*Persistency Curves of Extinction of Light on a Retina differently stimulated by White Light.*

SSN.	220°.	120°.	20°.	Dark adapted.
60	1·6	6·9	24	·18
58	5·3	13·6	40	·58
56	10	33	64·6	1·51
54	20	50	87·1	4·17
52	33·1	66	98	9·33
50	52·5	80	98	20·4
48	66·1	89	87	39·5
46	81·3	98	64	65
44	89·1	98	45·7	92
42	100	83·2	36·3	99
40	100	66	25·1	100
38	89·1	54	20	97
36	72·6	41·7	13·1	87
34	56·2	30·2	11·1	74
32	40	23·5	7·8	55
30	33	18·2	5·5	39·8
28	27	14·2	3·9	26
26	22·4	11·2	3	17
24	18·2	9·1	2·5	11·8

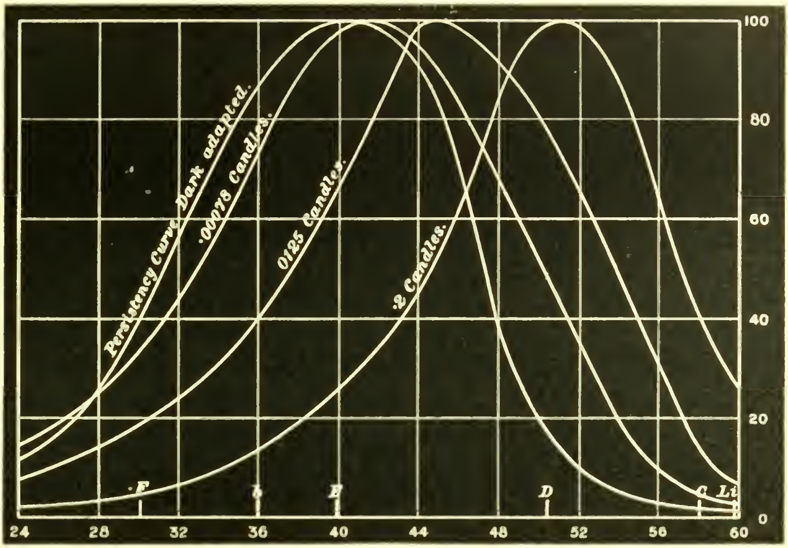


FIG. 65.

The extinction of the light depends on the size of spot of light, and appears to follow the same law as when the eye is dark adapted.

CHAPTER XIII

COLOUR FIELDS[1]

In Chapter II. was given an illustration of the colour blindness of the outside portions of the retina, and perhaps it is as a type of colour blindness that the phenomena is most interesting to the physicist, though to the ophthalmologist a contracted field may indicate something which helps the diagnosis of disease. In this chapter the treatment of colour fields will be entirely confined to results obtained with normal eyes and with pure spectrum colours, the eye *being dark adapted.* It will be seen in due course that the consideration of the laws which, though empyric, govern the extent of the fields, have something to say in confirmation of the trichromatic theory of colour vision.

Colour Fields.

[Perhaps the first thing that should be explained is what a colour field is. In the experiment cited in Chapter II., the experimenter, in order to lose sight of a spot of colour, was told to look at the spot and then move his head to the right and left without altering the direction of the eyes, and at a certain angle which the axis of the eyes made with the line joining the spot and the eye, the colour of the

[1] In this chapter the luminosities are given in terms of an amyl-acetate lamp (AL.), which may be taken, as already stated, as the light of 1 standard candle.

spot disappeared. Had the experimenter been told to move the head up and down, other angles would have been found at which the spot disappeared. Again, at other meridians, the same thing would occur. If the angles were measured and a chart made with the centre of the eye as the centre of the chart, and circles indicating the angles from the centre, and the meridians being indicated by lines intersecting the centre, then these observations would be charted and we should have a colour field.

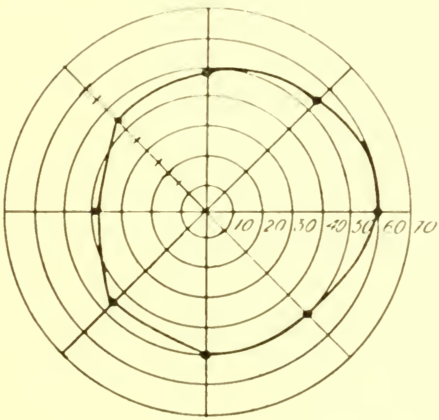


FIG. 66.

In the figure we have such a chart, and we give supposititious angles which the experimenter made in moving his head. Suppose, right and left, the right eye had to be turned 60° and 40° respectively, and up and down 50° each, and in the meridians at 45° on each side of the vertical axis, at 55° and 45° and 50° and 42°, the chart of the field for the ray, when it became colourless, would be as above, being indicated by the dark thick line. The chart might have been made slightly more complicated

by giving the angles as they would be projected on the surface of a hemisphere. The different diameters would also be increased in number, every 10° being indicated. These are not the charts which we shall use in this chapter, though the meridional angles of the field will be increased so that every 30° are shown.]

Apparatus for Testing Colour Fields.

In order to obtain the colour fields of pure colour special apparatus is required. Two forms were employed by the writer. The first was a perimeter of ordinary form, but modified for use in a dark room. The perimeter of the form employed is an instrument consisting essentially of a semi-circular iron or brass band which was graduated into degrees about 2 in. in width, which can rotate round a pin or axis piercing the centre of the metal band. There is a double chin rest, on which, if the chin is placed in one hollow, one eye is at the centre of the sphere, of which the semi-circular band is a portion ; if the chin be placed in the other side of the rest, the other eye occupies a similar position. The diameter of the sphere is about 30 inches. To adapt this for the spectrum colours, a mirror fastened to a ball-and-socket joint is placed just below the position occupied by the eye, *i.e.* just below the centre of the sphere. By means of an arm the mirror can reflect along the arc any beam of light falling on it. The light reflected was so arranged that a circular spot of any desired colour could be caused to travel along the arc (which was covered with white) when it occupied any angle with the vertical. The distance of the arc was so arranged that the image of the first surface of the first prism was in focus on it, and the spot was formed

by placing a diaphragm against the prism. The intensity of the colour could be altered—(1) by closing or opening the slit through which the coloured ray issued; (2) by placing a graduated annulus in front of the slit; (3) by closing the slit of the collimator; (4) by using sectors in front of either slit. The mode of observation was to cover up one eye, and the other eye was at the centre of the sphere when the chin was on the appropriate rest. A spot of coloured light was caused to travel along the white band of the semi-circle whilst the eye was directed to its centre, which was marked by a pin point of Balmain's luminous paint. When the colour of the light was judged to have gone, the reading of the arc was taken. It was not very difficult to cause one coloured spot and one white spot to travel side by side, and this enabled an accurate observation of the disappearance of colour from the spot under consideration to be taken. This was usually unnecessary, as the judgment as to the disappearance of the colour without the comparison spot was very accurate.

In the second form of perimeter, a hollow white hemisphere made of "papier mâché" was employed. The centre of the surface was pierced with a circular aperture some $1\frac{1}{2}$ in. in diameter. This aperture was closed by a doubly-ground glass, and outside the shell apertures of any desired shape or dimensions could be placed in contact with the ground glass. The colour patch apparatus was caused to throw the patch of colour on to the ground glass. When the glass was removed, the patch of white that the combining lens cast when the whole spectrum was uncovered, fell upon the eye when placed at the centre of the hemisphere. This insured that every ray was fully received on the pupil

when the ground glass was again interposed. It may be stated here, once for all, that when light falling on the ground glass was measured, by placing a white card in its place and balancing it with an amyl-acetate lamp, it was found that the brightness of the ground glass, as seen from the centre of the hemisphere, was,

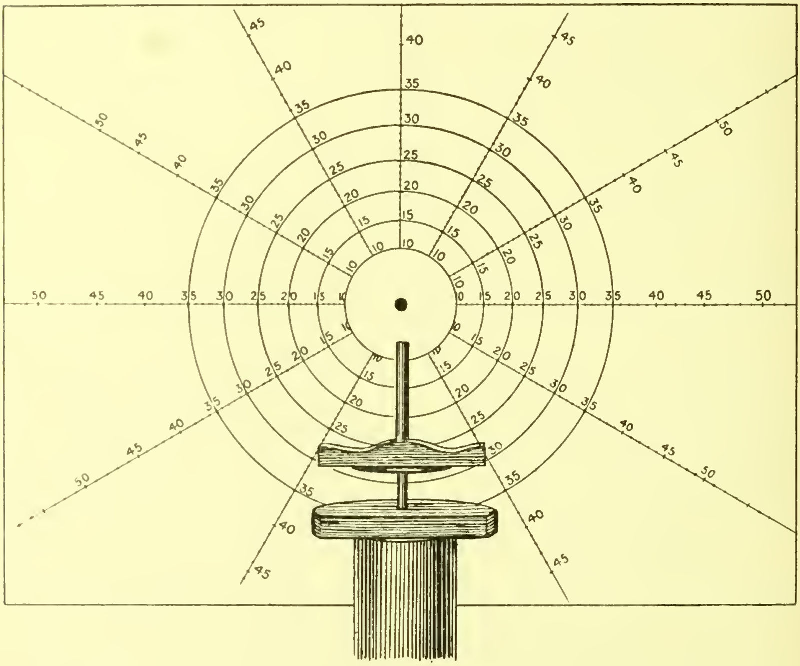


Fig. 67.

within a very small fraction, twelve times that which was reflected from the white card.

The hemisphere was furnished with a chin and cheek rest, which would move round a vertical axis. It was divided internally into degrees. The eye was directed to any part of the surface by means of a small phosphorescent bead at the end of a stick ; and a small

electric lamp, which could be switched on by a simple movement of the hand, gave light sufficient to read the position occupied by the bead at any desired instant. The intensity of the light illuminating the ground glass was altered by any of the four methods mentioned above. The annulus was usually employed to effect the alteration, and it could be rotated at the will of the observer by a long handle attached to the rack and pinion motion of the rotating gear.

Instead of the hemisphere a flat surface was also used, as in Fig. 67. The circles were drawn as shown, and the faint guiding light was moved along the different meridians, the colour being seen at the centre. The chin-rest is shown. This method is very simple and effective.

Similarity of Fields for Different Colours.

It was essential to know whether the fields for each colour were of the same form when the illumination was so adjusted that one point in a field of one colour coincided with one point in the field of a different colour. The following two sets of observations made by the writer, and the succeeding ones by one of his assistants (W. B.), will give the answer to the inquiry.

An aperture of ·525 in., subtending an angle 2° 30′, was inserted behind the ground glass, and the light falling on the eye when D was the ray selected, was 4·5 amyl-acetate lamps, nearly equivalent to 4·5 candles, at 1 ft. (In future this light will be designated as AL., and this particular illumination would be 4·5 AL.)

The following rays were used to illuminate the

aperture: red lithium (λ 6705), D (λ 5892), a ray having the standard scale number 36 (λ 5085), and the blue

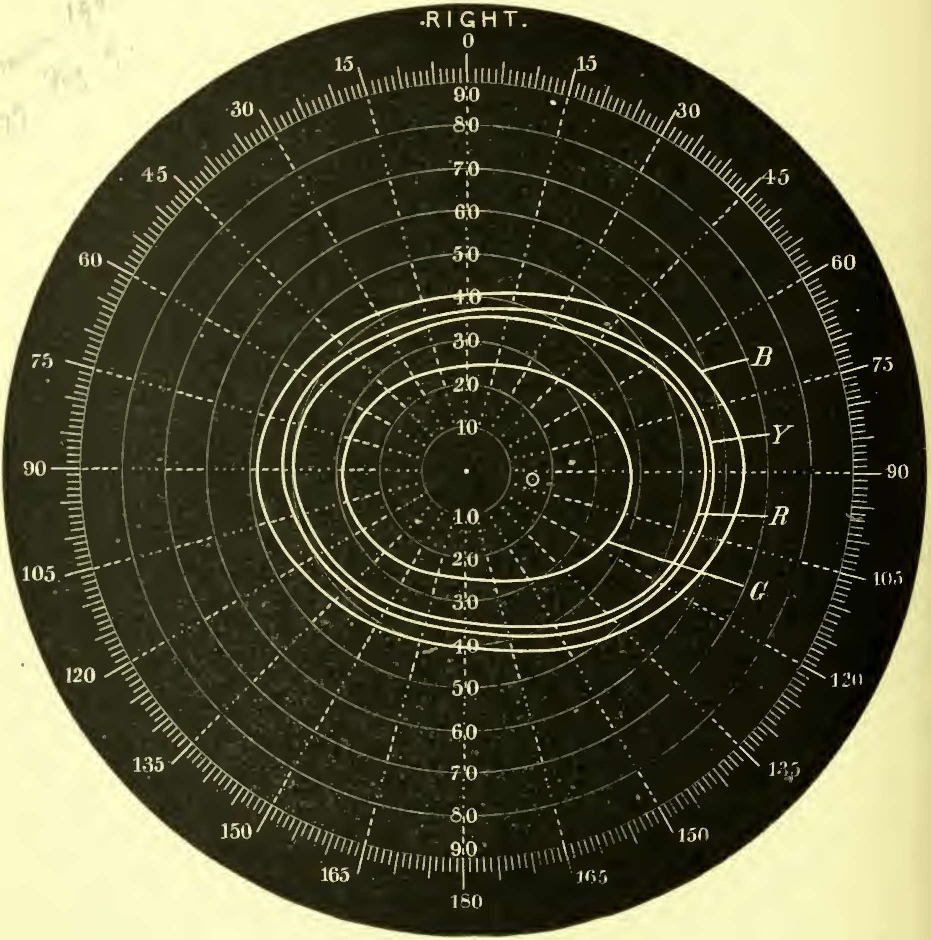


Fig. 68.

lithium ray (λ 4603). These had respectively the luminosities of ·3, 4·5, 2·1, and ·4 AL.

The measures were made with the right eye (see Fig. 68).

TABLE XXVII.

Angle of Field in Degrees.	Extent of Fields in Degrees.			
	Red Li.	D.	SSN. 36.	Blue Li.
0	35	36	24	40
30 T.	37	40	27	47
60 T.	47	50	33	57
90 T.	55	57	38	65
120 T.	51	53	36	60
150 T.	41	43	29	50
180	34	36	25	40
150 N.	35	36	26	40
120 N.	37	38	27	45
90 N.	40	42	28	49
60 N.	38	40	27	45
30 N.	34	36	25	42

T. is the temporal and N. the nasal side of the retina.

In the following observations the illumination by the D light was much reduced, being only ·23 AL., and for certain reasons, which will be apparent, the ray at scale number 41·7 was substituted for that at scale number 36. The other three were the same as before (Fig. 69).

TABLE XXVIII.

Angle of Field in Degrees.	Extent of Fields in Degrees.			
	Red Li.	D.	SSN. 41·7.	Blue Li.
0	23	25	15	28
30 T.	28	27	16	32
60 T.	35	37	21	40
90 T.	38	40	23	47
120 T.	35	37	22	42
150 T.	27	30	18	35
180	23	25	16	28
150 N.	25	26	16	29
120 N.	28	30	18	32
90 N.	29	30	18	34
60 N.	26	27	17	30
38 N.	23	25	16	28

Taking these sets of observations separately, the diagrams show that the fields for properly selected luminosities are evidently the same, the D and red

Fig. 69.

lithium being very close to one another. If we compare the fields for the D and red lithium rays in the second table with that of the field for the green (SSN. 36) in

the first table, we shall see that they are practically identical.

The next measurements were made by a different

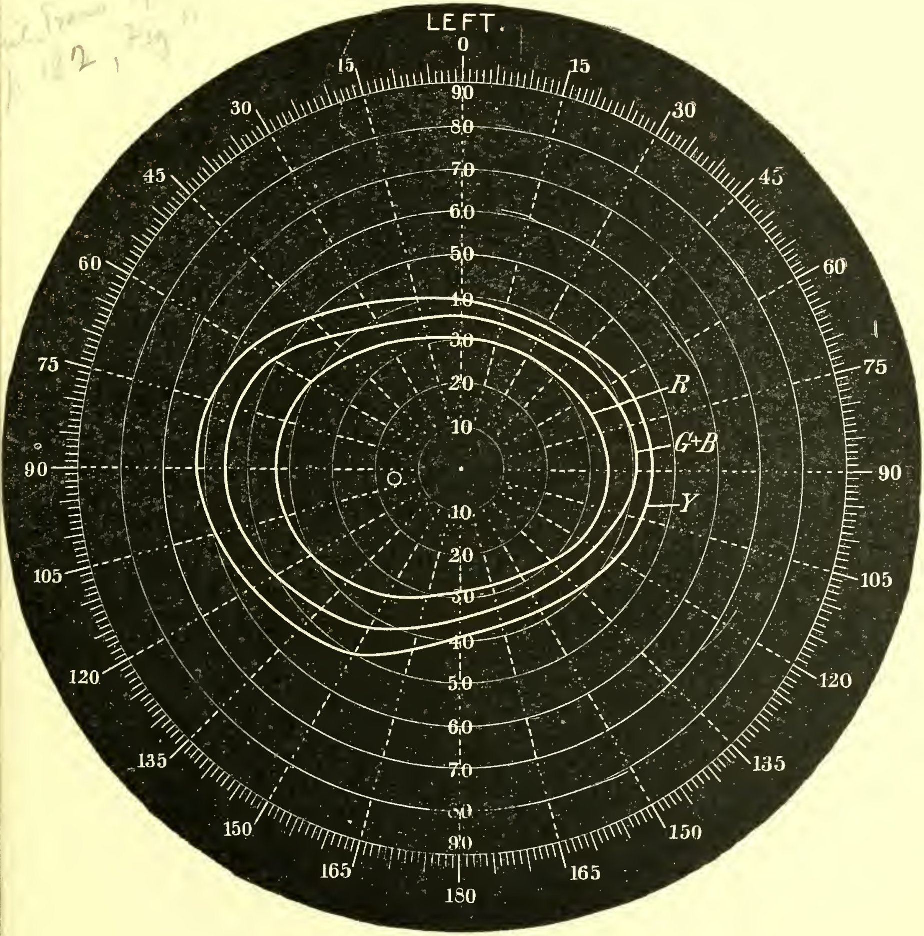


FIG. 70.

person, and since, as before stated, his colour fields vary considerably from the writer's, the confirmation obtained by his measurements appears very conclusive. They

were made for illustrating a different part of the research, but they will be given here and referred to subsequently. Two places in the spectrum were selected, such that the two rays when combined would give white light, the white being that of the electric light, which is practically indistinguishable from the sensation produced by the coloured rays when falling on the peripheral portions of the retina. The first positions selected were in the red and green, at λ 6500 and λ 5002, corresponding to the scale of the spectrum with the numbers 57·8 and 34. The relative luminosities of the rays reaching the eye were 225 and 270 respectively.

Two other positions were chosen in the yellow-green at λ 5614, and in the blue at λ 4603, corresponding to the scale numbers of the spectrum 46·3 and 22·8. The relative luminosities of the rays transmitted to the eye were 96·5 and 21·5 respectively.

The colour field for each of these four colours was taken with the left eye, and the following table shows the results (Fig. 70) :—

TABLE XXIX.

Angle of Field in Degrees.	Extent of Fields in Degrees.			
	Red.	Green.	Yellow-green.	Blue.
0	30	35	39	36
30 N.	28	34	37	35
60 N.	31	37	42	38
90 N.	33	40	44	41
120 N.	32	36	42	37
150 N.	28	34	38	34
180	29	35	39	36
150 T.	34	43	50	44
120 T.	40	50	57	50
90 T.	43	55	62	55
60 T.	41	51	56	50
30 T.	33	38	43	39

Here we have two fields, the green and the blue, which are practically identical, showing that the limits of the boundaries are not affected by the hue, though, of course, the illumination is very different in the two cases.

Fields of Impure or Mixed Colours.

When considering the question of the fields of mixed colours, such as those produced by pigments, it became apparent that a crucial test as to their efficiency might be made by mixing colours of the spectrum together to imitate some single spectrum colour, and, after making the mixture of the same luminosity, to compare the fields. With this in view, a red and green, near E, were mixed together to match the D light in hue and in intensity. The fields for each colour, including D, were taken, as also was that of the mixed colours.

The following table gives the results :—

TABLE XXX.

Angle of Field in Degrees.		Extent of Field in Degrees.			
		Red.	Green.	G + R. (Matching D.)	D.
0	N.	35	36	33	38
30	N.	35	35	33	36
60	N.	36	36	35	39
90	N.	39	41	37	43
120	N.	37	38	37	42
150	N.	35	35	34	37
180		37	38	35	38
150	T.	43	46	40	47
120	T.	49	51	45	50
90	T.	56	58	50	61
60	T.	50	52	46	53
30	T.	39	40	35	42

These colour fields all have the same shape (Fig. 71). They do not cut one another, and if we compare the

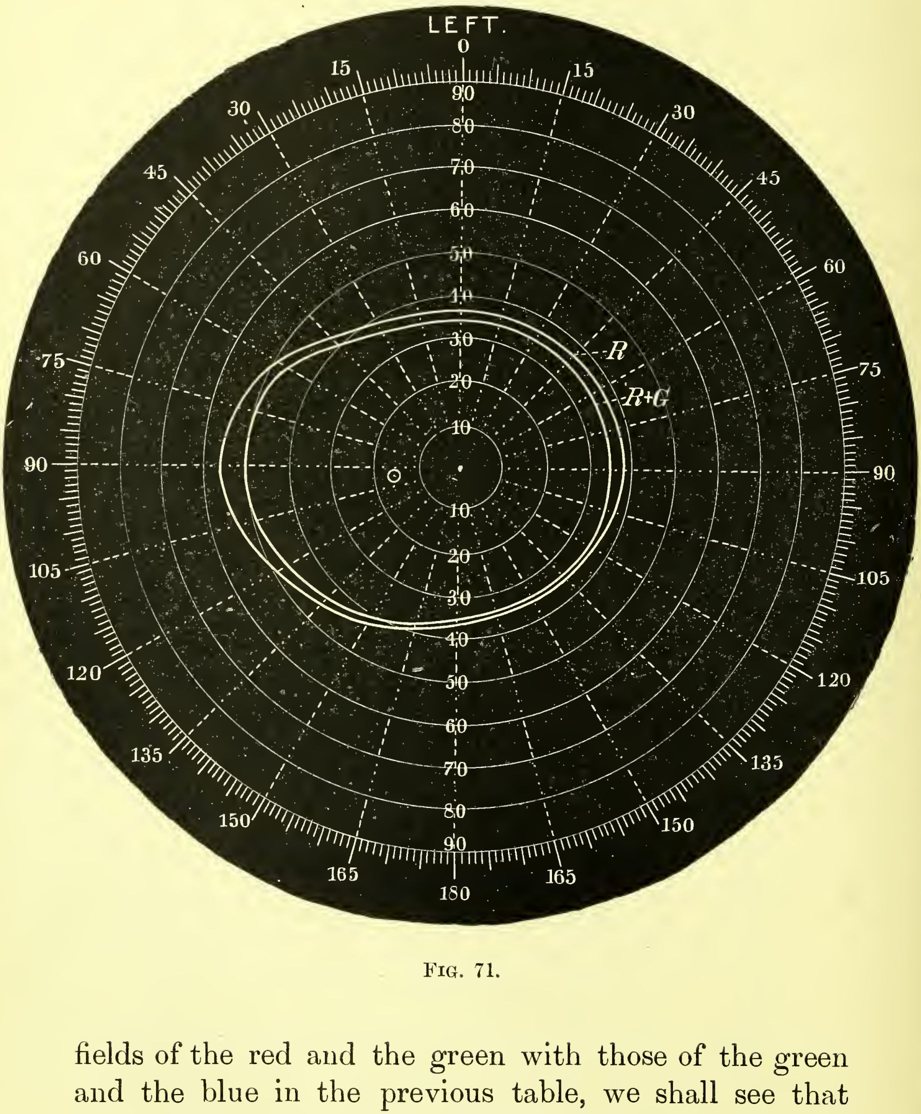


Fig. 71.

fields of the red and the green with those of the green and the blue in the previous table, we shall see that they practically coincide. Thus the fields of a red, two

greens, and a blue are the same when proper luminosities are taken for each. Before leaving this table, it is well to point out that the field for D is considerably more extended than that of the mixed colours, as are also the fields for green and red separately. We may conclude that the intrinsic white light in each colour, when added together, is greater than the intrinsic white light in the D ray, which has been shown to be the case in the chapter on colour equations. Colours of pigments should therefore not give the same fields as the spectrum colours with which they approximately match, since they are impure colours.

Connection between Change of Intensity of Colour and Extent of Field.

The difference in extent of field, caused by difference in illumination, was next determined in the *horizontal* directions. The four rays—red lithium, D, scale number 41·7 in the green, and the blue lithium—were experimented with as being fairly representative of the whole spectrum. The different rays were first allowed to pass through the annulus at 0°; and subsequently measures were made after passing through it, when its readings were 35, 70, . . . 280°, as every added 35° halved the previous intensity. The D light coming through the slit with the annulus at 0°, measured 4·5 AL. The following were the luminosities of the other rays coming through the same slit: red lithium, ·5 AL.; SSN. (41·7), 3·2 AL.; and blue lithium, ·3 AL.

TABLE XXXI.

Degrees Annulus.	Intensity of Ray.	Reading of Horizontal Field in Degrees.							
		Red Lithium.		D.		Scale No. 41·7.		Blue Lithium.	
		Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.
0	1	54	42	57	45	43	33	61	48
35	$\frac{1}{2}$	50	38	53	41	39	29	57	44
70	$\frac{1}{4}$	47	36	49	37	35	27	53	42
105	$\frac{1}{8}$	43	32	45	34	32	24	50	38
140	$\frac{1}{16}$	39	29	41	31	28	22	46	34
175	$\frac{1}{32}$	35	26	37	28	25	19	42	31
210	$\frac{1}{64}$	32	24	33	26	21	16	39	29
245	$\frac{1}{128}$	28	20	30	23	17	14	35	26
280	$\frac{1}{256}$	24	18	26	20	14	13	31	25

We find from the above that the average diminution in field for each reduction of half intensity on the temporal side is 3·75°, and on the nasal side close upon 3° (see Fig. 72). Using these figures, the above table, would be as follows:—

TABLE XXXII.

Degrees Annulus.	Intensity of Ray.	Reading of Horizontal Field in Degrees.							
		Red Lithium.		D.		Scale No. 41·7.		Blue Lithium.	
		Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.
0	1	54	42	57	45	43	33	61	48
35	$\frac{1}{2}$	50·25	39	53·25	42	39·25	30	57·25	45
70	$\frac{1}{4}$	46·5	36	49·5	39	35·5	27	53·5	42
105	$\frac{1}{8}$	42·75	33	45·75	36	31·75	24	49·75	39
140	$\frac{1}{16}$	39	30	42	33	28	21	46	36
175	$\frac{1}{32}$	35·25	27	38·25	30	24·25	18	42·25	33
210	$\frac{1}{64}$	31·5	24	34·05	27	20·5	15	38·5	30
245	$\frac{1}{128}$	27·75	21	30·57	24	16·75	12	34·75	27
280	$\frac{1}{256}$	24	18	27	21	13	9	31	24

With W. B. these numbers became 4 and 2·5 respectively, showing a consistent variation from our own measures. With other eyes it may be expected that the numbers will also vary, but it appears that

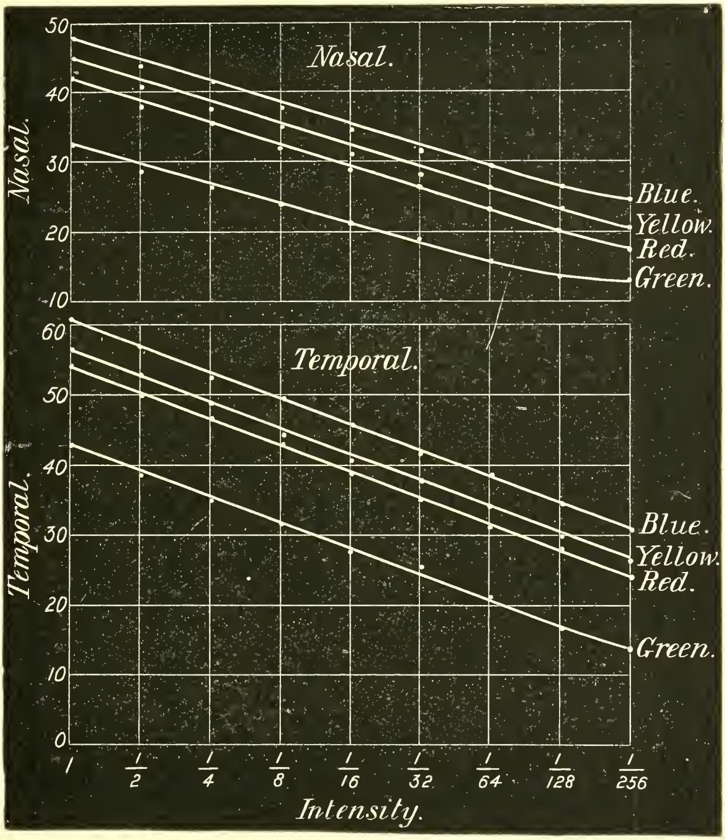


FIG. 72.

there is a diminution in the angle of field in an arithmetical progression, as the intensity diminishes in geometrical progression. The region of the macula lutea was avoided in these observations, as it seemed to be useless to attempt any observations on a part of the retina which was evidently unsuited for them.

Extent of Field for the Different Rays of the Spectrum.

Another set of experiments were carried out to ascertain the extent of the colour fields for all colours

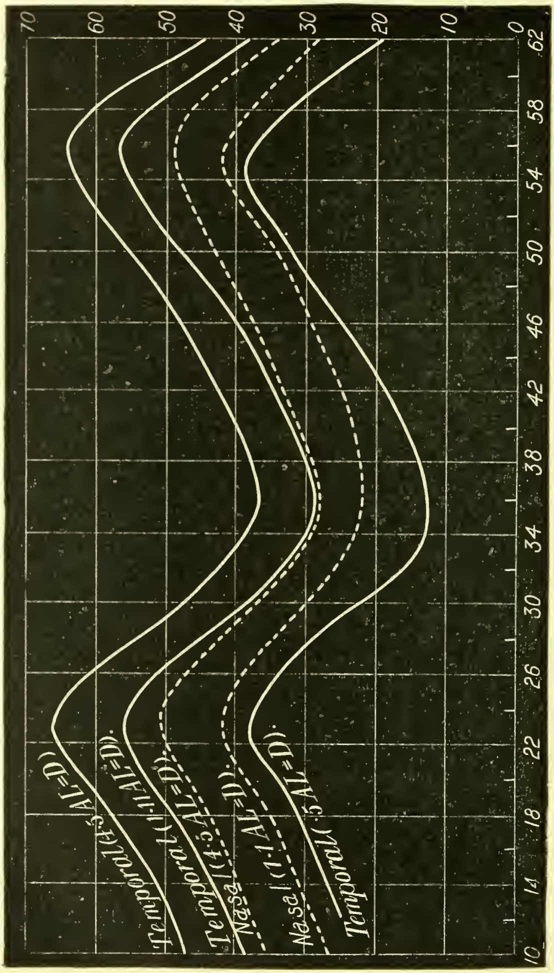


FIG. 73.

when a slit was passed unaltered through the spectrum. The following is a table of three sets of observations

taken by the writer. The two first were taken with an aperture of ·525 in., with an angular value of 2° 30′. The third was taken with an aperture of ·086 in., embracing an angle of 25′ only, the temporal extent being only observed with it. The luminosity of the D light for each set of observations is given in the column of remarks in the table.

TABLE XXXIII.

Scale No.	λ.	No. 1.		No. 2.		No. 3.	Remarks.
		Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	
62	6957	44	34	37	28	18	The luminosity of the D light in No. 1 = 4·5 AL.; an aperture of ·525 in. was used at 1 ft. distance.
60	6728	53	41	45	33	27	
58	6520	61	47	53	37	33	
56	6330	64	49	56	41	38	
54	6152	63	48	55	41	39	The luminosity of the D light in No. 2 = 1·1 AL., with an aperture of ·525 in.
52	5996	60	46	52	38	36	
50	5850	56	43	48	35	33	
48	5720	52	40	44	32	29	The luminosity of the D light in No. 3 was ·5 AL., an aperture of ·086 in. being used at 1 ft.
46	5596	49	38	40	30	25	
44	5481	46	35	37	28	22	
42	5373	43	33	34	26	18†	
40	5270	40	31	32	24	16†	
38	5172	38	29	30	23	14†	The readings marked † were doubtful, as they fell on or close to the blind spot. They were obtained by reading at a small angle to the horizontal line.
36	5085	37	28	29	22	13†	
34	5002	39	29	30	23	13†	
32	4929	42	32	33	25	16†	
30	4848	47	36	39	30	21	
28	4776	54	42	45	35	28	
26	4707	61	47	52	39	34	
24	4639	65	50	56	42	37	
22	4578	65	50	55	42	38	
20	4517	61	47	53	39	34	
18	4459	58	44	49	35	31	
16	4404	54	41	46	33	29	
14	4393	51	39	43	31	27	
12	4296	49	38	41	29	25	
10	4245	47	36	39	27	...	

If we plot the curves from the above table, and take the distance apart of the nasal from the temporal ordinates, we shall find that when the latter reads 40° the former reads 30°, no matter what the colour may be; and that, when the field increases about 7½° on the temporal side, the field on the nasal side increases nearly 6°—a variation which is in accordance with the table showing the field with variation of intensities of the beam (Fig. 72).

Dependence of Field on the Size of the Coloured Spot.

In Chapter XII. it has been shown that the loss of colour in the centre of the retina depends largely on the size of the spot of light viewed. Such being the case, it

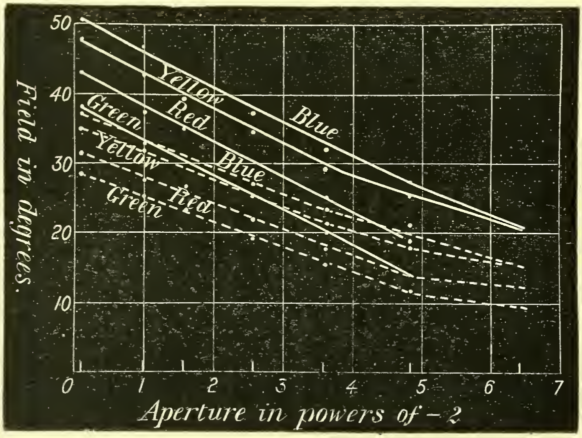


Fig. 74.

seemed probable that the boundaries of a field would contract if the spot of light dependent on the aperture used in the apparatus was diminished, and if so, it

seemed possible that some expression might be found which might connect the two together.

The same kind of perimeter was employed as before, and the spot of light on the ground glass was diminished in size by placing circular apertures of diminishing diameter in contact with it. The fields were measured in a horizontal direction only at first, and the following table gives the mean of the actual measures. The intensity of the D light was 1·1 AL.

TABLE XXXIV.

Diameter of Aperture in Inches.	Angle Subtended.	Diameter of Aperture in Powers of 2.	Red Lithium.		D.		41·7.		Blue Lithium.	
			Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.	Temporal.	Nasal.
	° ′ ″									
·94	4 18 0	− ·09	42	32	48	35	38	28	50	37
·525	2 30 0	− ·93	37	28	43	32	33	25	47	34
·35	1 34 0	− 1·52	35	26	39	29	31	23	42	31
·17	0 49 0	− 2·56	29	22	34	25	25	18·5	37	27
·086	0 25 0	− 3·56	25	17·5	29	21	20	15	32	23
·036	0 10 0	− 4·8	19	14	25	18	*b.s.*	12	27	21
·012	0 3 30	− 6·4	*b.s.*	12·5	20	15	*b.s.*	9	20	15

b.s. is blind spot, where measures are impracticable.

This table, when plotted, gives a diagram (Fig. 74) which shows that between apertures subtending 4° 28′ and 10′ (the power of ½ being taken for the scale of abscissæ), the fields decrease in extent and are practically straight lines. For each diminution in aperture to ½ diameter, the diminution *in field*, on the temporal side, is 5°, and on the nasal side 4°. The diminution in field for a diminution of ¼ the intensity *of light*, it will be remembered, is 7·5° on the temporal side and 6° on the nasal side. The diminutions in field thus bear the same ratio to one another, viz. 5 : 4. The diminution by every ¼ of the area is thus equivalent to ¼ of the

intensity of light. From p. 155, Chapter XII., this might be expected, but the writer was by no means prepared to find that the relationship could be measured so closely. When the apertures used were greater than the largest given in the table, scarcely any alteration of the field was obtained. And it may be taken that to the writer any aperture subtending more than 5° will give the same field. And with apertures subtended between 5° and 3°, the field will only slightly diminish.

CHAPTER XIV

THE THEORY OF COLOUR VISION

In the preceding pages it has been shown how the luminosity of a colour can be measured, and the luminosity of a bright spectrum has by this means been ascertained. It has also been shown that the luminosity of a spectrum, when of a feeble character, fails to be able to stimulate the red sufficiently to compare with the stimulation given by the other parts of the spectrum, and that the maximum luminosity is no longer found in the yellow, but is in the green, and that the colours are all more or less degraded in hue, being more grey than coloured, and finally, when the source of light used for forming the spectrum or the spectrum itself is dimmed, the last trace of light is to be found in the green. Again, it has been shown that after all colour has disappeared from the different rays a residual light is left, and that by proper appliances this residual light itself may be extinguished; though, from the nature of the experiments, some radiation still is extant, though insufficient to stimulate the retina. Further, it has been shown that the same absence of colour is found when a fairly bright ray is received on a part of the retina which is not central, and that for each different ray we have a colour field the extent of which depends on the brightness of the rays and on the size of section of the beam which falls upon the retina.

These phenomena, together with others which are

found in colour blindness, have to be explained by any theory which is to be accepted. The physicist naturally looks at the matter from a physical standpoint, and the physiologist, equally naturally, regards it from a physiological aspect. The true aspect must be that to which both agree. The seat of colour sensation, whether in the brain or on the retina, is an open question which neither side of scientific thought has established. This is a question which by-and-by will no doubt be settled, but in the meantime the physicist at all events must be content to utilise the hypothesis that the primary seat and sensation is in the retina, which is an outcrop of the brain. Mathematicians treated the mysterious ether, on the oscillations of which our colour sense depends much in the same way. The theory that is offered in these pages is the trichromatic theory of colour vision, which, from the physicist's point of view, explains completely the various phenomena met with. The trichromatic theory was first propounded by Young, who was at the time professor at the Royal Institution. He based it on the postulate that there are three primary colours in the spectrum, a primary colour being one which is incapable of being matched by mixture of any other colours, and that all the other spectrum colours could be imitated by a mixture of two or three of the primaries. In 1861 Clerk Maxwell took up the Young theory, and was enabled by an ingenious apparatus which he devised, to show by calculation from observed measures the composition of the spectrum colours in terms of the three arbitrarily chosen primary colours. In the next chapter these observations and measures will be discussed. It is right to observe here that from his calculations he was the first to show that the three colours need not necessarily be the primary

sensations of colour, but that stimulation of one or more of the three sensations could account for all colours.

Helmholtz followed Maxwell, and, as in all other branches of science, he added largely to our knowledge of the phenomena of colour vision. In his laboratory Kœnig worked out the form of the three sensations' curves, indicating the strength of the sensations called into play by the various spectrum colours. The writer next attacked the problem, and published two separate sets of curves.[1] An account of the more recent determination of the sensations will be found in the next chapter. The trichromatic theory, then, is a theory which recognises only three colour sensations, and regards every colour as the result of the stimulation of one, two, or three of these sensations, and, it may be added, it can also include what may be called the fundamental sensation of light. In the broad aspect of the theory, where colour is of moderate brightness, this last is an unnecessary addition, as any effect the fundamental sensation may have is drowned by the greater brightness of the colour. When the colours are not bright, as in a feeble spectrum, the fundamental light has to find a place in the theory. The theory reduces colours to their very simplest form, and this is quite in accordance with the method in which nature works. It is quite open for other theories to be propounded in which certain groups of colours in the spectrum are supposed to be separately produced, but which fail when analysed by mathematical considerations. Again, every spectrum ray may be supposed to be a separate sensation, but there is not warrant for such extravagance.

[1] See Papers Nos. 5 and 6.

Helmholtz's Sensation Curves.

Helmholtz suggested that every ray in the spectrum affected each of the three sensations of red, green, and blue. His idea is shown in the figure. The top curve is supposed to be the red sensation; its height at various parts of the spectrum is supposed to indicate the amount of stimulus given to the sensation by each ray of the spectrum. Similarly, Nos. 2 and 3 curves are supposed

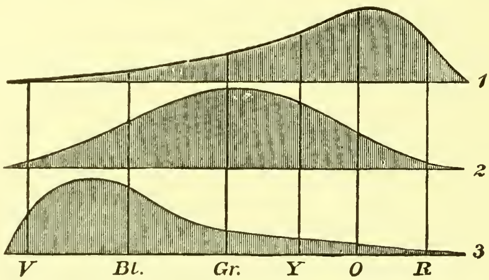


FIG. 75.—Helmholtz's Colour Sensation.

1. Red sensation.
2. Green sensation.
3. Blue sensation.

to represent the green and blue stimulation by the different spectrum rays.

It will be seen shortly that Helmholtz's idea was right in the main, though perhaps not quite exact in certain details, when the subject is considered in the light of modern researches.

The sensations which are excited must be due to some action on sensitive apparatus which lie at the base of the retina. It might be a mechanical action or a chemical or an electrical action which causes the sensation. It is most likely to be caused by a chemical action, which, as we know, induces electrical action, and

which is really a mechanical action from the molecular point of view. How this action stimulates each of the sensations is at present by no means settled. In any case there must be some receiving apparatus in the retina on which the light falls, and the energy of the light converted into visual sensations. Be the apparatus what it may, we have first to satisfy ourselves that the impact of the spectrum on the retina can produce curves of sensation such as are shown in Helmholtz's figure.

Action of Nonsynchronous Rays on the Sensation Apparatus.

We can quite understand why a coloured ray can cause a chemical decomposition of a substance in which the rhythmic excursions of an atom or atoms from the centre of attraction in a molecule are in exact tune with the waves of light falling on such atoms. The excursions may be so increased in extent by the rhythmic energy supplied by the waves of light that the atoms leave the molecule and give us a new molecule. Possibly by the electric current set up, the sensation of the colour is produced. But it is not so easy to see why the rhythmic excursions of atoms in the same molecule are also increased to the point of molecular rupture when the wave-motion of the impinging rays are not quite "in tune" with the rhythmic excursions.

Photographic and Mechanical Examples.

If a sensitive salt, say the chloride of silver, be exposed to the action of the spectrum, on development we have a streak of reduced silver which varies in density

of deposit throughout its length. By careful measurement of the opacities of the deposit at different points, and then referring them to a scale of graduation obtained by developing a plate which has been exposed to known intensities of light, we are able to make a curve which shows the sensitiveness of the particular salt of silver to the different rays of the spectrum. We have in

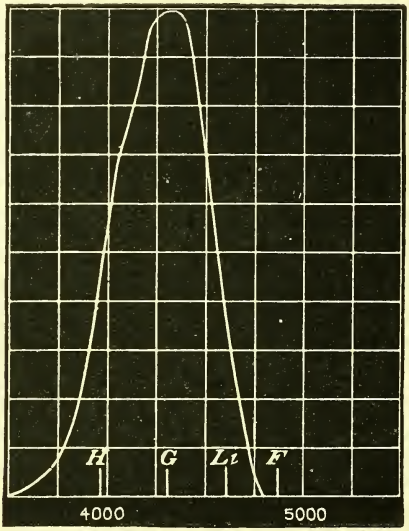


Fig. 76.—Effect of Spectrum on Silver Chloride.

Fig. 76 the curve of sensitiveness of silver chloride, and in Fig. 77 that of silver bromide to the different rays of the spectrum. The place of maximum sensitiveness is different in the two cases. If we mix the two salts together, we should get a curve which is compounded of the two curves. If a third silver salt had been impressed, we should have a place of still different maximum, and the curve of sensitiveness of the three mixed silver salts would be one compounded of the

curves of all three salts. If we can account for the curve of sensitiveness of any one of the silver salts, the reason of the curves of sensitiveness of any other salt will be the same.

The fact is that the maximum of the curves show the place in the spectrum where the vibrations causing the ray are in tune with the vibrations of the chlorine

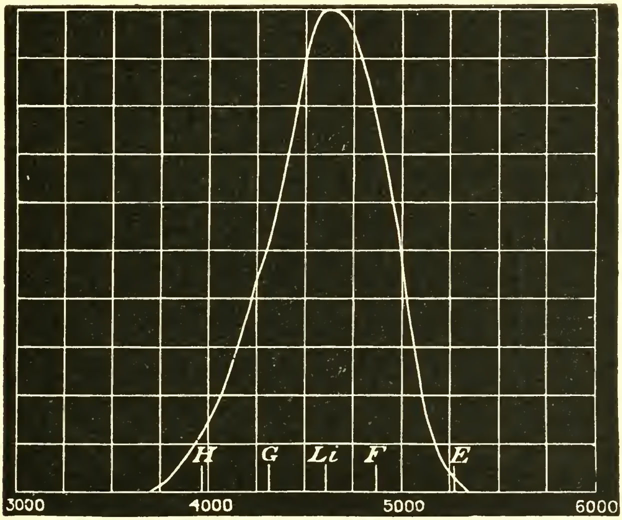


Fig. 77.—Effect of Spectrum on Silver Bromide.

in the silver chloride, the chlorine being that part of the molecule which is swung away and annexed to some other adjacent foreign molecule. We may also take a mechanical example of the effect produced by vibrations which are not in tune with, but have to act on, a vibrating body. A simple apparatus, in which two different pendulums are caused to act on one another, one having a very light bob and the other a heavier one, will be such an example. The first pen-

dulum may be taken as representing the chlorine atom, and the other the ray of light. When the two pendulums are of equal length and the heavy one is started vibrating, the light one also begins to swing, and as it is in tune with the vibrations of the first, the amplitude constantly increases. Making the light-bob pendulum a little longer or shorter than the other, and again starting the swing of the latter, the lighter one commences to swing. At first the heavy one will cause it to swing with increasing amplitude, but by degrees the two will begin to swing in opposite directions; the amplitude of the light pendulum will decrease and finally come to rest, when it starts again as before. The annexed figure shows the trace that the light pendulum

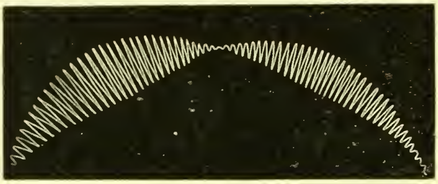


FIG. 78.

makes when acted upon by the heavy one. The increase in amplitude is well marked, as is the period when it comes to rest. Thus if the waves causing a ray of light are out of tune with the atom's vibration, the amplitude will still be increased; and the increase can be such as to swing the atom beyond the sphere of molecular attraction, and so decomposes the molecule, but with less facility than when the waves of light are "in tune."

Resonator Curves.

Helmholtz has also shown that in the case of sound acting on a resonator, not only does that sound which

has the same period of vibration as the resonator set it in vibration, but that sounds which differ slightly in wave-motion from that which is synchronous with it also set the resonator vibrating. He shows that the greater difference there is between the synchronous sound and that applied, the less does the resonator respond. The curve in which he shows the difference in resonation is similar to that of those shown in Figs. 66 and 67.

We see, then, that we may expect when the spectrum falls upon what we may call a visual receiving apparatus, that not only will such apparatus respond to the ray whose waves are "in tune" with it, but that waves on each side of it will also cause it to respond, though to a smaller extent, and that the general shape of the curves would be the same as found for a photographic simple salt. In some cases we might expect that principal harmonics might also give curves of lesser ordinates.

We shall find when the sensation curves are discussed in detail, as they will be in the next chapter, that what has been supposed might be expected seems to be found in one of them.

Dazzling Colours.

Before quitting the photographic simile, we may notice what happens to a photographic image of the spectrum when for moderate brightness a dazzling brightness is substituted and the same exposure given. Measuring the opacities of the different parts of the developed image, we shall find that the top of the curve is nearly flat for some distance on each side of the place of maximum sensitiveness, instead of being a rounded point. This flat top indicates that the silver salt has

been exhausted of its atoms, which are swung away, and that the maximum decomposition has been obtained by rays which are not "in tune" with the atomic swing.

The effect of a dazzling coloured light should be similar. All three sensations are stimulated by, say, a green ray, the green stimulation being in preponderance. If a dazzling green ray falls on a place in the retina, we have the green sensation at its maximum stimulation at once, and following quickly on we have the red and blue sensations contained in the ray at their maximum stimulation. When the three stimulations are equal, the effect is to produce the sensation of white. The green would thus appear nearly white, with a slight tinge of green in it. From the sensation composition of an orange ray, which is red and green, we should find, on using the same argument, that the dazzle colour of the orange would be a very bright yellow of a hue in which the two stimulated sensations are equal.

Visual Receiving Apparatus.

At the present time it is almost useless to discuss the nature of the visual receiving apparatus, as opinions differ in the physiological world even as to the functions of the rods and cones in the retina. It may, however, be said that to the physicist there is a strong inclination to believe that there is some substance or substances attached to or inherent in retinal processes which have the power of being altered by light waves. The first thought is naturally that the visual purple[1] might be such a substance, since it has been proved that it bleaches in the light. *Prima facie* it has to

[1] It is not found existing in some fully developed eyes which are presumed to see colours.

be rejected on the grounds that its absorption spectrum is that of a purple ; therefore it absorbs the green rays and allows the red and blue to be transmitted. Where there is such absorption as the visual purple possesses, a chemical or heating action must take place, chiefly in the green and but slightly in the red, yellow, and blue, so that the effect of the green would be most visualised, but the fact that every ray of the visible spectrum is visualised, and that the yellow is most luminous, makes it appear that we must look for a more universally absorbing substance. A physicist would have to look perhaps for some grey matter, composed of triple molecules, which would absorb the rays which evoke the three sensations. One molecule might be of a nature to call forth the red, the second the green, and the third the blue sensations, which might be visualised by an electric current evolved as the result of the chemical action. In case of complete colour blindness, one of the three molecules might be inert (as is the case in some cases of photographic salts of silver, which become insensitive by special preparation); or, in the case of incomplete colour blindness, one might be less capable of chemical decomposition. The vibrations of the compounded molecule as a whole might cause the visibility of the fundamental sensation of light. The "Purkinje effect" has been described at p. 146. It must be pointed out that a similar effect is found in a photographic plate which is rendered sensitive to the whole spectrum. Such a plate, when exposed to a fairly bright spectrum, can be caused to show a negative in which every colour will give the same density of deposit. If everything remains the same, except that the brightness of the spectrum is very much diminished (but though the time

of exposure is prolonged to meet the diminished brightness), the resulting negative [1] will show the red as having very little density compared with the blue and the green. Should the visual sensations be primarily due to the chemical decomposition of some substance on the retina, it would not be unexpected, if the retina exhibited the same characteristics as found in the photographic plate. This is one form which might account for the visualisation of the three sensations, but, as said before, it is only a guess, and we must leave it to the physiologist to give a lead. Coming to the facts which give evidence of the truth of the three-sensation theory, we can mention one: that knowing the amount of stimulation of the sensations which is given by any two spectrum rays, we at once can tell the colour and the luminosity of the colour which they will give by mixture in any proportions. As we proceed to consider the phenomena exhibited in colour vision, circumstantial evidence of the truth of the theory will be offered from its power of explaining them in the simplest of manners. There are extant theories that account for the different phenomena exhibited by colour vision on a psychological basis which at once removes them from the "ken" of any exact science. There is also one theory amongst others which postulates more than three single sensations. This must stand or fall on the evidence afforded by observations, amongst them being those which are recorded in this work.

[1] See Paper No. 29.

CHAPTER XV

THE COLOUR SENSATIONS

WE can commence the practical demonstration of the trichromatic theory of colour vision with a reference to Clerk Maxwell's observations.

Clerk Maxwell's Colour Apparatus.

The instrument he employed is shown in Fig. 79. The apparatus[1] really was a spectroscope, somewhat

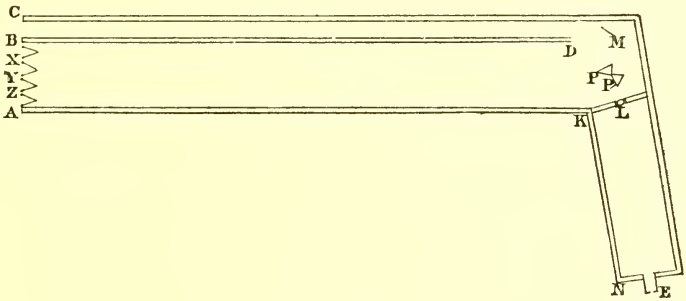


FIG. 79.

the same as the colour patch apparatus described in Chapter IV., but the paths of the rays are reversed in the way in which it was used. In a screen at D (see Fig. 79), three slits (X, Y, and Z) were placed, which were viewed from the position which the collimator slit occupies. One slit was placed in the position that a red would occupy in the spectrum if light were sent

[1] The second instrument he employed was based on the first one, which we describe.

through the collimator, another in the green, and the third in the blue. If the three slits were illuminated by diffused light and the eye were placed at what would be the collimator slit E—when the slit Y in the green was alone opened—looking through L it would see the surface of the prism P illuminated with a spectrum green ; if the red or the blue were only open, then the prism would appear illuminated by red or blue. When all three slits were open, the colour seen would be a mixture of all three rays. Clerk Maxwell caused a white card, on which sunlight fell, to illuminate the slits. A comparison white light was also furnished by a light from a sunlit card passing between B and C, but which did not pass through the prisms, but was reflected by a mirror M. This white light was seen as a square patch alongside the illuminated prisms. The colour seen in the prisms of course depended on the position of the slit or slits which were open.

With this apparatus Maxwell made his observations. In the first instance, the three slits were placed in positions which he selected empyrically as standard ones. One slit illuminated the prism with a "good" red when viewed from the eye aperture, another with a "good" green, and the third with a "good" blue. The slits were then opened or closed until the prism was illuminated with a white which matched the "comparison" white in hue and brightness. He next kept two of the slits in the standard positions and moved the third into different parts of the spectrum, and again matched the white as before. This slit was then replaced in the standard position and one of the other slits was moved in the spectrum, and again matches of white made. Finally, the slit which had not been moved was moved, the other two being in

the standard positions, and matches once more made. From these observations equations were formed that included the position of the slits and its measured aperture.

Maxwell's Colour Equations.

The following table contains the means of four sets of observations by an observer, Clerk Maxwell, called K, and is typical of his mode of procedure :—

TABLE XXXV.

$$\begin{gathered}
44{\cdot}3(20)+31{\cdot}0(44)+27{\cdot}7(68)=W \\
16{\cdot}1(28)+25{\cdot}6(44)+30{\cdot}6(68)=W \\
22{\cdot}0(32)+12{\cdot}1(44)+30{\cdot}6(68)=W \\
6{\cdot}4(24)+25{\cdot}2(36)+31{\cdot}3(68)=W \\
15{\cdot}3(24)+26{\cdot}0(40)+30{\cdot}7(68)=W \\
19{\cdot}8(24)+35{\cdot}0(46)+30{\cdot}2(68)=W \\
21{\cdot}2(24)+41{\cdot}4(48)+27{\cdot}0(68)=W \\
22{\cdot}0(24)+62{\cdot}0(52)+13{\cdot}0(68)=W \\
21{\cdot}7(24)+10{\cdot}4(44)+61{\cdot}7(56)=W \\
20{\cdot}5(24)+23{\cdot}7(44)+40{\cdot}5(60)=W \\
19{\cdot}7(24)+30{\cdot}3(44)+33{\cdot}7(64)=W \\
18{\cdot}0(24)+31{\cdot}2(44)+32{\cdot}3(72)=W \\
17{\cdot}5(24)+30{\cdot}7(44)+44{\cdot}0(76)=W \\
18{\cdot}3(24)+33{\cdot}2(44)+63{\cdot}7(80)=W
\end{gathered}$$

(The figures in brackets indicate the place in the spectrum the slits occupied. W is white, always of the same value, which was matched by the mixed colours.)

These equations were referred to the standard equation, which was the mean of twenty observations with the slits at the standard places (24), (44), and (68)—

$$18{\cdot}6(24)+31{\cdot}4(44)+30{\cdot}5(68)=W$$

Incidentally Maxwell remarked that from these twenty equations the mean error of the red was ·54,

of the green 1·22, and of the blue 1·15, whilst the error of mixture of R, G, and B to make white was 2·67. The mean error in *differences* of the amount of two colours in a mixture is only about ·85, and as the hue of the mixture depends on the ratios of the components, whilst the brightness (luminosity) depends upon their sum, it appeared to him that the eye is a more accurate judge of the identity of colour in two parts of the field of view than of their equal illumination.

By eliminating W from the fourteen equations in the table by means of the standard equation, the different rays of the spectrum are shown in terms of the three standard colours he selected, and are as follows :—

TABLE XXXVI.

$$
\begin{array}{rl}
 & \quad (24) \quad (44) \quad (68) \\
44{\cdot}3(20) = & 18{\cdot}6 + 0{\cdot}4 + 2{\cdot}8 \\
16{\cdot}1(28) = & 18{\cdot}6 + 5{\cdot}8 - 0{\cdot}1 \\
22{\cdot}0(32) = & 18{\cdot}6 + 19{\cdot}3 - 0{\cdot}1 \\
25{\cdot}2(36) = & 12{\cdot}2 + 31{\cdot}4 - 0{\cdot}8 \\
26{\cdot}0(40) = & 3{\cdot}3 + 31{\cdot}4 - 0{\cdot}2 \\
 & \\
35{\cdot}0(46) = & -1{\cdot}2 + 31{\cdot}4 + 0{\cdot}3 \\
41{\cdot}4(48) = & -2{\cdot}6 + 31{\cdot}4 + 3{\cdot}5 \\
62{\cdot}0(52) = & -3{\cdot}4 + 31{\cdot}4 + 17{\cdot}5 \\
61{\cdot}7(56) = & -3{\cdot}1 + 21{\cdot}0 + 30{\cdot}5 \\
40{\cdot}5(60) = & -1{\cdot}9 + 7{\cdot}7 + 30{\cdot}5 \\
 & \\
33{\cdot}7(64) = & -1{\cdot}1 + 1{\cdot}1 + 30{\cdot}5 \\
32{\cdot}3(72) = & +{\cdot}6 + 0{\cdot}2 + 30{\cdot}5 \\
44{\cdot}0(76) = & +1{\cdot}1 + 0{\cdot}7 + 30{\cdot}5 \\
63{\cdot}7(80) = & +0{\cdot}3 - 1{\cdot}8 + 30{\cdot}5
\end{array}
$$

(The three standard colours are of course omitted, as they would be equated to themselves.)

The figure shows the results of the equations diagrammatically as given by Maxwell.

It will be noticed that there are parts of the three curves below the base line. These are the negative quantities in the equations after the left-hand members have been reduced to unity. We shall find that these negative quantities are due to the fact that most of the spectrum colours contain an appreciable quantity of

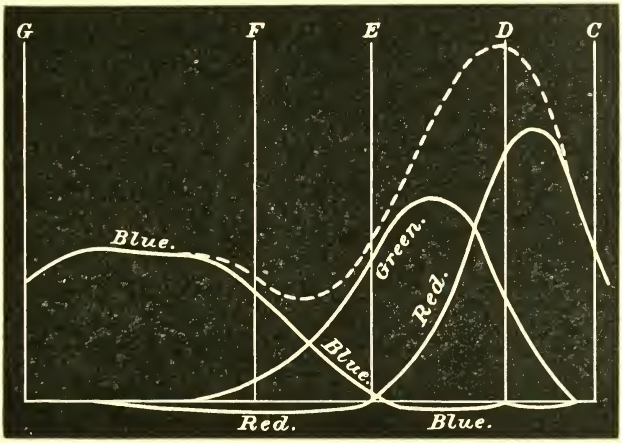


FIG. 80.

white. If this white were deducted from the white which the colours matched, the negative values would be non-existent. (The addition of the ordinates to one another to make a luminosity curve is rather misleading, as it is only the *widths of slits* and not the *luminosities* which are added together.)

Maxwell's Slit Apertures turned into Luminosities.

An attempt to turn these measures into a true luminosity curve has been made by using the luminosities of Maxwell's three standard rays, as found in the solar spectrum of a mid-day sun in June and also

in October, and an example is given. That the two curves differ is not surprising when the table is scrutinised. The width of the slit through which the red rays pass is the same for the first three numbers. From (36) to (52) the green rays have also the same apertures of slit, as also have the blue rays from (56) to (80). We shall see that the proportions are not quite the same if they are compared with the sensation curves given later on.

The equations are made so that the left-hand member is unity, and the right-hand members are multiplied by the following luminosities of the three standard colours :—

(24) is SSN. 56·3 having a luminosity of 40·3
(44) „ 40 „ „ 63
(68) „ 20·3 „ „ 2·5

Table XXXVII.

Maxwell's Scale.	SSN.	Luminosity.	Measured Solar Spectrum Luminosity.
(20)	59·6	18	·3
(23)	56·3	40·3	40·3
(28)	53	70	75
(32)	49·8	90	99
(36)	46·5	98	94·5
(40)	43·2	81·2	81
(44)	40	63	63
(46)	38·3	52	54
(48)	36·7	45	41·5
(52)	33·4	30·4	21
(56)	30·1	20·6	11·5
(60)	26·9	11·9	6·8
(64)	23·6	2·2	4·4
(68)	20·3	2·5	2·5
(72)	17·1	3·3	1·7
(76)	13·8	3·7	1·2
(80)	10·5	—·4	·8

Colour Sensations.

We will now proceed to describe the method by which the writer worked out his own colour sensations. It may here be stated that the writer's colour sense is normal, as is also his form vision.

First of all, let us place a slit in the red near the extreme end of one spectrum, and in a second spectrum, as formed by the apparatus described at p. 44, let us place another slit in a movable slide, so that it can be put in any part of the second spectrum desired; and let us place the two patches side by side. Let a sector be placed in the path of the second spectrum's rays. If we place the slit at SSN. 58, which is a red, and equalise the luminosity of the two patches, we shall find a slight difference in hue. If we move the slit to 60, we shall find that the hues of the two patches are the same. Such is the case at SSN.'s 61, 62, and 63, the first slit being at SSN. 64 (with a piece of red glass in front of the slit to destroy the effect of any stray light which may be about). Thus we may take it that a slit placed anywhere from a little above SSN.'s 60 to 64 will show the same hue, and this includes the place which the red line of the vapour of lithium occupies when the salt is volatilised in the arc or is heated in a spirit or gas flame. As regards the violet of the spectrum, it similarly appears to be of one uniform tint throughout when the necessary precautions are taken to prevent its contamination by any white light which may come from the illumination of the prisms. If we take a slice of violet light from the spectrum and form a patch with it from one spectrum, and mix a very minute portion of white light with it, we shall find that it becomes lavender coloured. When therefore repeating the experiments

made at the red end in the violet, it is well to place in front of the slit a piece of cobalt blue glass or ammonia sulphate of copper. This cuts off the green, and very nearly all the yellow and red, but allows the violet to pass, so that any contamination is a minimum, all the brightest parts of the spectrum being cut off from any small quantity of white light which may struggle through the slit. When this precaution is taken, it is found that the hue of the region from near G in the solar spectrum upwards is the same, the only difference being its brightness at the different parts. But violet is not a primary colour, for if we take a patch of violet light from one spectrum and place one slit in the red near the red lithium line, and another in the blue near the blue lithium line, we can make a mixture of red and blue which will match the violet, to which a little white has been added. We shall see hereafter that the blue itself contains a large percentage of white, and for this reason white has to be added to the violet. This tells us that as we require pure colours —*i.e.* unmixed with white as far as possible—for making colour mixtures, it is as well to use violet as one colour (remembering that it is a definite mixture of red and blue), in preference to the blue, which is contaminated by inherent white. When a mixture is made, the violet can always be converted into blue and red, and the latter be added to the red which may be in the mixture.

Colours not identical with Colour Sensations.

So far we have been dealing only with colours, and not with colour *sensations*. If Helmholtz's diagram, p. 214, were correct, one colour would never stimulate one sensation by itself. As it is, however, the red

stimulates only the red sensation in one part of the spectrum, whilst the violet stimulates both the red and blue, and not the green sensations. A green colour not only stimulates the green sensation, but it stimulates the red and blue sensations as well, as is shown in Helmholtz's diagram. The trichromatic sensation theory requires this to be the case.

That there is white mixed with the purest green, we shall demonstrate experimentally. Now, white involves the stimulation of all three sensations, so that no green can represent the pure green sensation to the normal vision, though, as we shall see, it can be felt by one form of colour blindness. White is the only mixture with a green sensation which can help us to realise most nearly the kind of sensation that it is, and one of the first searches to be made is to find some colour in which this is the only admixture.

Equal Stimulations of the Three Sensations to produce White.[1]

It is well, as a preliminary, to consider the sensation of white as the result of the equal stimulation of the red, green, and violet perceiving apparatus, remembering, of course, that the violet is compounded in definite proportions of red and blue sensations. We may use it as a temporary sensation without objection if this be remembered.

We can then construct diagrams which will show what points in the spectrum can be fixed by preliminary observations.

A, B, and C are the most interesting cases. Let the stimulation of the sensations be represented by vertical lines. In A we have the red and green sensations of

[1] See Papers Nos. 5 and 6.

equal heights, but V is less. Drawing a horizontal line through *c*, *a*R, *b*G, and *c*V, represent equal stimulations which make white, leaving *da* and *eb* equal. We thus have a colour which is made up of a mixture of R and G sensations (RS. and GS.), together with white. Now, equal stimulation of RS. and GS., we shall see later, give the sensation of yellow. If we place a slit in the violet and move it along the less refrangible part of the spectrum, we shall find a place where this colour and violet together make a white (the slits are opened or

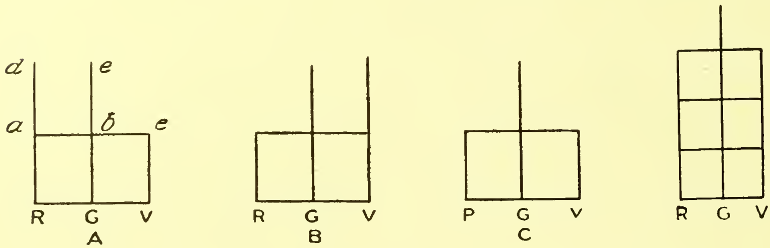


Fig. 81.

closed to make the match). This position, then, is that in which the red and green sensations are equally stimulated, and answers to A. In B we have a green and violet with equal ordinates and a deficiency of red. If we place a slit in the red and move another about in the green, we shall find a colour which with the red makes white. This position, then, will have an equal stimulation of green and violet. This gives another fixed point. The next point to determine is diagrammatically shown by C, which illustrates the green we have to look for, mixed only with white. This is more difficult to find, as it would require a purple to be added to make a match with the white, and this does not exist in the spectrum. Suppose we mix A with B, we get a diagram of the kind shown in the fourth dia-

gram. There are equal reds and violets stimulated, but a larger stimulation of green sensation. This gives a colour paler than the spectrum colour, but still a green which can be matched. There are also other plans dependent on trial and error of fixing this point which can be carried out. (There is also a confirmation which can be made by a green-blind person, of which we shall speak presently.) At any rate, we have several data with which to commence a series of observations.

Conditions to be observed in making Measures.

There are several considerations that have to be taken into account in making measures. In the first place, the white light used must be of the same "quality"—that is, the relative luminosities of the different rays of its spectrum must be constant. Secondly, the measures are best made with the central part of the retina, and the patches of mixed light should be the same size and be viewed from the same distance throughout. The light from the crater of the positive pole of the arc light is always of the same quality, and is best adapted for a standard light when colour patches have to be viewed; and in fixing the points in the spectrum the above conditions should be carefully carried out.

When the observations[1] for obtaining the fixed points have been made, it will be found that the colour which with violet makes white is at SSN. 48·7, that the colour which with red makes white is at SSN. 34·6, and that where the green, mixed only with white is found, will be SSN. 37·5. With these three points fixed,

[1] The following observations were made with the spectrum of the crater of the arc light with sloping carbons.

and the knowledge that the red stimulates a pure sensation of red, and the violet sensations of blue and red unmixed with green, we can begin to find the sensations which exist in other colours. What first is required is to know the amount of white which exists in the green at SSN. 37·5. To ascertain this we must place one slit at SSN. 37·5 and another at, say, SSN. 59·8, the position of the red lithium line. The luminosities of these two colours with equally wide slits must be taken, say, against a neutral colour, such as yellow or white. They will be found to be 39·2 and 9·4 respectively. A patch of orange light from the second spectrum is placed alongside the patch of mixed red and green, and an endeavour must be made to get the same *hue* of orange-yellow in the mixture. It will be found that the mixed lights are always paler than the spectrum colour. White light is next added to the latter until the same paleness of hue is produced.

The widths of the slits are measured and the luminosity of the white added is determined. An equation is formed in luminosities thus—

$$a \text{ (yellow)} + b \text{ (white)} = c \text{ (red)} + d \text{ (green)}$$

Now, the red contains no white, so all the white that is in the mixture must be white contained in the green colour. The equation comes out—

$$a \text{ (yellow)} = c \text{ (red)} + [d \text{ (green)} - b \text{ (white)}]$$

That is, the percentage of white in the green is $\frac{b}{d} \times 100$,

and the percentage of green sensation is $\frac{(d-b)}{d} \times 100$.

When these equations have been worked out, it will be found that the white (obtained from the mean of

several equations) in SSN. 37·5 is 69 per cent. of the luminosity. The following is a concrete example of the observations made. A yellow was taken at SSN. 50·05, and the following equation in luminosities obtained :—

$$\begin{array}{cccc} \text{RS.} & (37{\cdot}5). & (50{\cdot}05). & \text{White.} \\ 48{\cdot}7 & +\ 45{\cdot}8 = & 63 & +\ 31{\cdot}5 \end{array}$$

As there is no white in the red sensation (RS.), it follows that the 31·5 white is in the SSN. 37·5. This gives—

$$\begin{array}{ccc} (50{\cdot}05). & \text{RS.} & \text{GS.} \\ 63 = & 48{\cdot}7 & +\ 14{\cdot}3 \end{array}$$

That is to say, from this equation there is 31·2 per cent. of GS. in 37·5 and the white in SSN. 37·5 is 68·8 per cent.

The composition of the orange and yellow regions of the spectrum was found by placing one slit in the red of the spectrum and another in the yellow or at D, the composition of these rays having been determined by the observations which were made to find the percentage of white in SSN. 37·5. Some dozen colours between SSN.'s 49 and 58 were determined in this way, bearing in mind the small corrections due to the shift in hue by the addition of white.

When once this percentage of white in the green has been arrived at, the percentage sensation composition in luminosities of the remaining colours can be readily found.

By putting three slits in the spectrum and fixing one in the violet about SSN. 10 and another at SSN. 59·8, and putting the third slit at different positions between SSN. 35·5 and SSN. 48·7, equations can be formed of the luminosities of the three colours necessary to match the white patch. Instead of altering the width of the slits

to make the luminosity the same as the white patch, sectors can be put in the path of the white beam and the luminosity of the white determined. The standard equation, *to which all other equations are referred*, is the equation given by placing the "green" slit at SSN. 37·5, the other two remaining as above. Thus an equation of this form is found—

Red.		Green.		Violet.		White.
a	+	b	+	c	=	d

We have to deduct 69 per cent. of white from the green on one side of the equation and the same amount from the other, which will give the white in terms of sensations only. It was found that the mean of the equations gave the following as the value of white in sensation luminosities (RS. and GS. standing for red and green sensations and V. for violet) :—

RS.		GS.		V.		White.
68·4	+	30·2	+	1 4	=	100

To this standard equation all other equations were equated. The following is an example of an observation, and the calculations by which the percentage composition in sensation luminosity of the ray in question was found. The ray whose composition was required to be found was SSN. 40. It was found that when the matched white was 100, the following was the equation, the apertures of the slits being multiplied by the luminosities :—

RS.		(40).		V.		White.
36·8	+	62·1	+	1·14	=	100

but—

RS.		GS.		V.		White.
68·4	+	30·2	+	1·4	=	100

this being the standard equation.

From these we get—

$$\begin{array}{cccc} (40). & \text{RS.} & \text{GS.} & \text{V.} \\ 100 = & 51 + & 48{\cdot}6 + & {\cdot}42 \end{array}$$

which is the percentage composition of SSN. 40. The composition of other rays between the red and SSN. 37·5 was found in the same way.

It was believed (until the change in hue caused by the addition of white to a colour was determined) that there was a plan by which the amount of violet in the SSN.'s from 37·5 to the red could be better determined than by the ordinary equations. The idea was to accurately determine the red to the green sensations by this last plan, and then to mix a red at the red lithium line with a green at 37·5 to match the hue of the colours within that region. The white contained in the green was known, and *prima facie* it was supposed that the violet necessary to form the white would be a correct measure of the violet to be found in the ray under consideration. The violet was in this way found, with the result that the sensation, instead of gradually diminishing towards SSN. 50, rose in the middle, and had a maximum about SSN. 42. This method evidently is inaccurate in consequence of the change in hue. For this reason the older method has had again to be resorted to and the violet determined from the mean of several separate equations.

From SSN. 36 to 12 a different method was adopted, which gave very accurate results. The composition of all rays from SSN. 64 to 37·5 is known from previous observation. If, then, we place a slit at some place having a lower SSN. than 36, we can find some colour which, when mixed with it, will give a white. (It is convenient in this observation to use the two spectra

given by the double colour patch apparatus described at p. 44.) The colour being found which makes the match, the slits are measured as usual, and the luminosity being known, a luminosity equation is formed. Take an example of SSN. 25·5. It was found that the ray at SSN. 49·05 gave the white. After converting the width of slits into luminosities, and reducing the equation so that white was 100, the following was obtained :—

$$\begin{array}{ccccc} (49\cdot05). & & (25\cdot5). & & \text{White.} \\ 96 & + & 4\cdot0 & = & 100 \end{array}$$

Now, from the percentages already determined—

$$\begin{array}{ccccc} \text{RS.} & & \text{GS.} & & (49\cdot05). \\ 70\cdot1 & + & 29\cdot9 & = & 100 \end{array}$$

after converting (49·05) 96 into RS. and GS., we get—

$$\begin{array}{ccccccc} \text{RS.} & & \text{GS.} & & (25\cdot5.) & & \\ 67\cdot30 & + & 28\cdot10 & + & 4\cdot00 & = & 100 \end{array}$$

Equating this with the standard equation, we get—

$$\begin{array}{ccccccc} 25\cdot5. & & \text{RS.} & & \text{GS.} & & \text{V.} \\ 100 & = & 27\cdot5 & + & 37\cdot5 & + & 35 \end{array}$$

In this manner the composition of all the SSN.'s smaller than SSN. 36 were calculated.

The method of finding the percentage sensations existing in each colour of the spectrum has now been shown, and from the determinations curves of red and green sensations and of violet were drawn as smooth curves. The ordinates of these curves are given in the following table in columns IV., V., and VI. Columns I., II., and III. are the scale numbers, the wave-lengths, and the luminosity of the rays for normal vision.

Columns VII., VIII., and IX. give the *luminosities* of the two sensations and violet, obtained by multiplying

TABLE XXXVIII.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.
Scale No.	λ.	Luminosity of Spectrum.	Percentage Composition.			Luminosity.			Percentage Composition.			Luminosity.			GS. ×2·3.	BS. × ·190.
			RS.	GS.	V.	RS.	GS.	V.	RS.	GS.	BS.	RS.	GS.	BS.		
64	7217	·5	100	...	...	·5	...	...	100	...	...	·5	...	...	...	...
62	6957	2	100	...	...	2	...	...	100	...	...	2	...	...	...	...
60	6728	7	100	...	...	7	...	...	100	...	...	7	...	...	...	...
58	6521	21	99	1	...	20·79	·21	...	99	1	...	20·79	·21	...	·48	...
56	6330	50	95·5	4·5	...	47·75	2·25	...	95·5	4·5	...	47·75	2·25	...	5·17	...
54	6152	80	90·5	9·5	...	72·40	7·60	...	90·5	9·5	...	72·40	7·60	...	17·48	...
52	5996	96	84·2	15·8	...	80·83	15·17	...	84·2	15·8	...	80·64	15·36	...	35·38	...
50	5850	100	75	25	...	75	25	...	75	25	...	75	25	...	57·5	...
48	5720	97	67	33	·07	65	31·93	·068	67·05	33	·020	65·16	32·01	·019	73·6	3·8
46	5596	87	62	37·9	·11	53·94	32·11	·095	62·03	37·9	·031	54·06	32·97	·027	75·9	5·13
44	5481	75	57·7	42·1	·15	43·77	30·81	·112	57·21	41·9	·042	43·30	31·50	·032	72·45	6·08
42	5373	62·5	54·9	44·9	·24	34·31	28·06	·150	55·04	44·9	·067	34·40	28·06	·042	65·23	8
40	5270	50	51	48·6	·42	25·50	24·30	·200	51·30	48·6	·117	25·61	24·30	·058	55·89	11·40
38	5172	36	48	51·3	·82	17·28	18·47	·260	48·52	51·3	·230	16·51	18·40	·083	42·32	15·77
36	5085	24	45	53·5	1·50	10·80	12·84	·360	46·08	53·5	·420	11·09	12·83	·101	29·51	19·19
34	5002	14·2	41·55	55·34	3·11	5·82	7·94	·442	43·79	55·34	·870	6·22	7·86	·124	18·08	23·56
32	4924	8·5	37·8	56·13	6·07	3·27	4·71	·516	42·17	56·13	1·700	3·58	4·77	·145	10·97	27·55
30	4848	5·7	34·10	54·60	11·28	2	3·08	·620	42·24	54·60	3·160	2·45	3·08	·174	7·08	33·06
28	4776	4	30·71	50·54	18·75	1·25	2·03	·720	44·36	50·54	5·200	1·76	2·03	·202	4·83	38·38
26	4707	2·8	27·70	41·30	31	·78	1·15	·868	50·02	41·30	8·680	1·41	1·15	·243	2·64	46·17
24	4639	1·95	24	28	48	·48	·53	·935	58·56	28	13·44	1·15	·53	·262	1·22	49·79
22	4578	1·4	20·2	16·3	63	·28	·24	·882	65·56	16·3	17·64	·91	·27	·247	·48	46·93
20	4517	1·1	16	8	76	·165	·10	·836	70·72	8	21·28	·77	·10	·234	·23	44·46
18	4459	·86	11·4	4·6	84	·098	·04	·720	71·88	4·6	23·52	·62	·04	·202	·092	38·38
16	4404	·70	6	2	92	·047	·01	·648	72	2	25·76	·51	·01	·180	·023	32·20
14	4349	·56	1·5	·5	98	...	...	·550	72	·5	27·44	·392	...	·154	...	29·26
12	4296	·45	...	...	100	...	...	·450	72	...	28	·334	...	·126	...	23·94
10	4245	·35	...	...	100	...	...	·350	72	...	28	·253	...	·098	...	18·62
8	4198	·26	...	...	100	...	...	·260	72	...	28	·187	...	·073	...	13·87
6	4151	·18	...	...	100	...	...	·180	72	...	28	·130	...	·051	...	9·69
4	4106	·14	...	...	100	...	...	·140	72	...	28	·101	...	·039	...	7·41
2	4062	·10	...	...	100	...	...	·100	72	...	28	·076	...	·028	...	5·32
0	4010	·06	...	...	100	...	...	·060	72	...	28	·057	...	·022	...	4·18

the percentages by the luminosities in column III., and dividing by 100. A series of observations made on the composition of the violet, show that it contains closely 72 per cent. of red sensation and 28 per cent. only of blue.

Columns X., XI., and XII. show the percentage composition in terms of the red (RS.), green (GS.), and blue (BS.) sensations. Column X. is column VII., to which 72 per cent. of the violet percentage has been added, and column XII. is 28 per cent. of the violet.

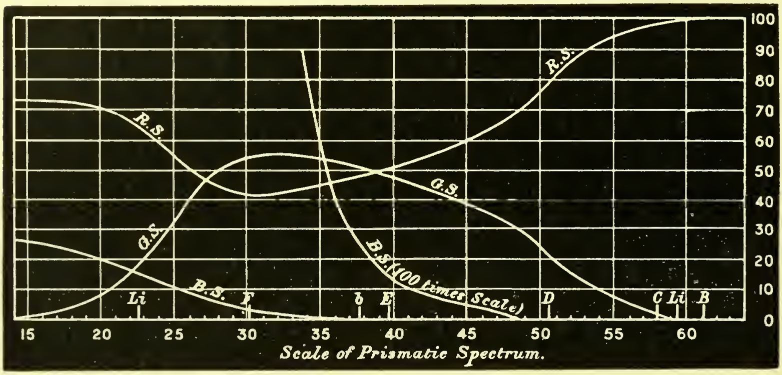


FIG. 82.—Percentage composition of the spectrum colours in luminosities of red, green, and blue sensations.

Columns XIII., XIV., and XV. show the luminosities in RS., GS., and BS., and columns XVI. and XVII. show columns XIV. and XV. multiplied by 2·3 and 190 respectively. These multipliers make the areas of all the three luminosity curves equal. Thus, columns XIII., XVI., and XVII. give the stimulations, when equal stimulations are supposed to give a sensation of white. We shall see that this is of some importance. Figure 83 shows the curves[1] of equal stimulation and Fig. (82)

[1] The percentage components of the sensations in terms of equal stimulation will be found in Chapter XXV.

the percentage curve in *luminosities* of the three sensations. At SSN. 48·6 we have the red and green curves cutting one another, which is one of the points we have already found. At 34·5 we have the intersection of the green and blue curves with the red curve below, and this is the point which with added red makes white, also previously determined.

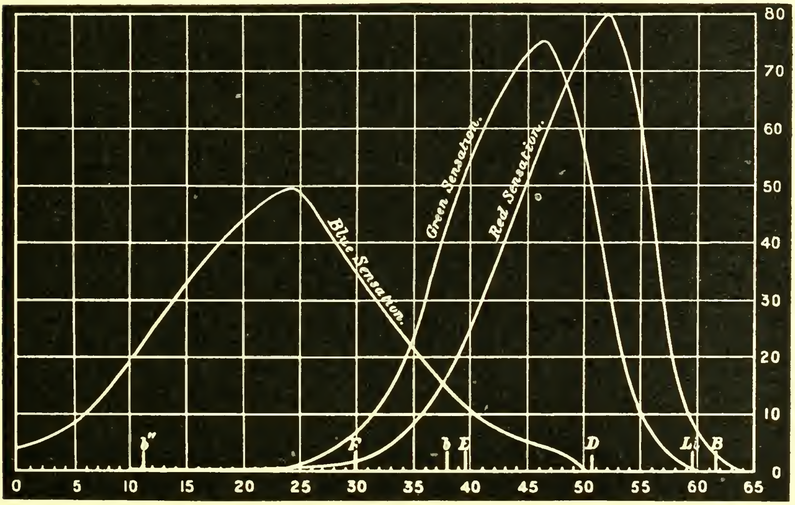


FIG. 83.—Sensation curves having equal areas (equal ordinates at any point make white).

At SSN. 37·5 we have the place where the green sensation is unmixed with anything except white, a position we have also previously determined. At this point the red and blue curves cut, and the green curve is here above the other two, showing that there is white and a surplus of green.

In Fig. 84 is shown the three sensations in terms of luminosity when the white has been deducted from them. This is drawn from Table XXXIX.

TABLE XXXIX.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SSN.	Luminosity of sensation together with the white.				Percentage composition of the sensations, white being deducted.		
	RS.	GS.	BS.	W.	RS.	GS.	BS.
64	·2	...	...	...	100	...	...
62	2	...	...	...	100	...	...
60	7	...	...	...	100	...	...
58	20·79	·21	...	...	99	1	...
56	47·75	2·25	...	...	95·5	4·5	...
54	72·4	7·6	...	...	90·5	9·5	...
52	80·64	15·36	...	...	84·2	15·8	...
50	75	25	...	...	75	25	...
48	61·4	30·3	...	5·3	66·9	33·1	...
46	54·1	30·8	...	7·1	63·7	36·3	...
44	37·2	28·8	...	9	56·4	43·6	...
42	26·4	24·9	...	11·2	48·6	51·4	...
40	14·2	19·3	...	16·5	42·4	57·6	...
38	·7	15·2	...	20·1	4·5	95·5	...
36	...	8	·031	16	...	99·6	·386
34	...	5·1	·088	9	...	98·31	1·69
32	...	3·2	·125	5·2	...	96·24	3·76
30	...	2·12	·155	3·43	...	93·18	6·82
28	...	1·33	·192	2·48	...	87·37	12·63
26	...	·53	·235	2·03	...	68·8	31·6
24	...	·03	·25	1·66	...	10·5	89·5
22	·43	...	·245	·73	15	...	85
20	·54	...	·235	·33	69·7	...	30·3
18	·51	...	·201	·15	71·8	...	28·2
16	·49	...	·18	·03	73·1	...	26·9
14	·39	...	·154	...	72	...	28
12	·334	...	·126	...	72	...	28
10	·253	...	·098	...	72	...	28
8	·187	...	·073	...	72	...	28
6	·13	...	·051	...	72	...	28
4	·101	...	·039	...	72	...	28
2	·072	...	·028	...	72	...	28
0	·057	...	·022	...	72	...	28
Areas.	450	192	2·53	187			

This table is useful to have by one, as it simplifies the calculation for obtaining the true dominant colours of pigments, &c. From columns XIII., XVI., and

XVII. of Table XXXVIII. the columns in this table are readily found.

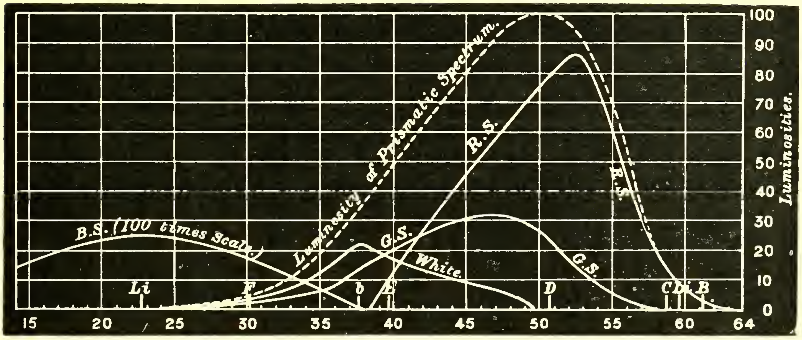


FIG. 84.—Luminosity curves of red, green, blue, and white sensations of the prismatic spectrum of the crater (positive pole) of the arc light.

[Taking SSN. 40, for instance, we find that SSN. 40 has—

Col. XIII. RS.	Col. XVI. GS.	Col. XVII. BS.
25·61	55·89	11·4

As equal ordinates make white, the smallest ordinate, 11·4 in this case, must be deducted from the other two to obtain the white, and we have left—

$$\begin{array}{ccc} \text{RS.} & & \text{GS.} \times 2{\cdot}3. \\ 14{\cdot}2 & \text{and} & 44{\cdot}5 \end{array}$$

Thus, after deducting 16·5 of white, the amounts of RS. and GS. are 14·2 and $\frac{35{\cdot}4}{2{\cdot}3}$, or 19·3, and the colour is denoted by the equation—

$$\begin{array}{ccccccc} \text{RS.} & & \text{GS.} & & \text{W.} & & \\ 14{\cdot}2 & + & 19{\cdot}3 & + & 16{\cdot}5 & = & 50 \end{array}$$

In the same way the equations for the other colours are calculated, and we have from the results Table XXXIX. and Fig. 84.]

The following tables show the luminosity composition —(1) of the arc light with horizontal positive pole; (2) of the Nernst lamp:—

TABLE XL.—*Sensation Luminosities*[1] *and Equal Stimulation Ordinates of an Arc Light with Horizontal Positive Pole.*

SSN.	λ.	Luminosity.	RS.	GS.	BS.	GS. × 2·21.	BS. × 117.
64	7217	·5	·5	...	...	...	...
62	6957	2	2	...	...	...	...
60	6728	8·7	8·7	...	...	...	...
58	6521	21·5	21·3	·2	...	·44	...
56	6330	48·3	46·1	2·2	...	4·86	...
54	6152	70	63·3	6·7	...	14·8	...
52	5996	84·7	71·3	13·4	...	29·61	...
50	5850	96·2	72·1	24·1	...	53·26	...
48	5720	99·9	67	32·9	·02	72·7	2·33
46	5596	95	59	36	·029	79·5	3·39
44	5481	85·3	49·7	35·6	·035	78·7	4·1
42	5373	72	39·6	32·3	·048	71·4	5·61
40	5270	56·1	29·1	27·	·076	59·8	8·89
38	5172	41	19·9	21	·094	46·3	11
36	5085	27·5	12·7	14·8	·11	32·5	12·8
34	5002	15·8	6·9	8·7	·127	19·3	14·8
32	4924	8·9	3·75	5	·151	11·1	17·6
30	4848	6·17	2·16	3·37	·195	7·45	22·8
28	4776	4·6	2·06	2·31	·247	5·1	28·9
26	4707	3·5	1·77	1·44	·307	3·18	35·9
24	4639	2·7	1·58	·76	·363	1·68	42·5
22	4578	2·16	1·4	·35	·381	·78	44·6
20	4517	1·76	1·24	·14	·378	·31	44·2
18	4459	1·48	1·07	·07	·36	·15	42·1
16	4404	1·29	·93	·03	·332	·06	38·9
14	4349	1·1	·79	·005	·302	·01	35·3
12	4296	1	·7	...	·27	...	31·6
10	4245	·85	·61	...	·288	...	27·8
8	4198	·73	·53	...	·204	...	23·8
6	4151	·62	·45	...	·174	...	20·3
4	4106	·5	·36	...	·14	...	16·4
2	4062	·4	·29	...	·112	...	13·1
0	4010	·3	·22	...	·084	...	9·8

[1] The percentage composition of the SSN.'s is the same as that given in Table XXXVIII.

TABLE XLI.—*Sensation Luminosities*[1] *and Equal Stimulation Ordinates of a Nernst Lamp Light.* 1 *amp.* 100 *vols.*

SSN.	λ.	Luminosity.	RS.	GS.	BS.	GS. × 2·77.	BS. × 254.
64	7217	1	1	...	...	...	...
62	6957	5	5	...	...	...	...
60	6728	12	12	...	...	...	...
58	6521	31·5	31·1	·4	...	1·1	...
56	6330	65	62·1	2·9	. .	8	...
54	6152	87·5	80·5	7	...	19·4	...
52	5996	99·7	83·9	15·8	...	43·7	...
50	5850	98·8	74·1	24·7	...	68·4	...
48	5720	89	59·7	29·4	·0178	81·4	4·52
46	5596	76·5	47·7	29	·0237	80·3	6·02
44	5481	61·5	35·7	25·8	·0258	71·4	6·56
42	5373	46·7	25	21	·0313	58·2	7·95
40	5270	35	18	17	·0410	47·1	10·41
38	5172	24·5	11·9	12·6	·0563	34·9	14·3
36	5085	15	6·9	8·1	·0630	22·4	16
34	5002	7·5	3·25	4·25	·0652	11·8	16·52
32	4924	4	1·66	2·24	·0680	6·2	17·27
30	4848	2·5	1·2	1·35	·0790	3·74	20·06
28	4776	1·8	·8	·91	·0936	2·52	23·77
26	4707	1·5	·75	·61	·1302	1·7	33·06
24	4639	1·25	·72	·35	·1680	·97	42·67
22	4578	1·05	·69	·16	·1852	·44	47·04
20	4517	·9	·64	·07	·1917	·19	48·68
18	4459	·75	·54	·03	·1262	·09	44·75
16	4404	·6	·43	...	·1560	...	39·62
14	4349	·5	·36	...	·1400	...	35·56
12	4296	·4	·28	...	·1120	...	28·44
10	4245	·35	·25	...	·0980	...	24·89
8	4198	·3	·22	...	·0840	...	21·34
6	4151	·25	·18	...	·0700	...	17·78
4	4106	·21	·15	...	·0588	...	15
2	4062	·18	·13	...	·0524	...	13·31
0	4010	·15	·11	...	·0420	...	10·67

It may be useful for reference to have the sensation luminosities of the normal spectrum in which the abscissæ

[1] The percentage composition of the SSN.'s is the same as that given in Table XXXVIII.

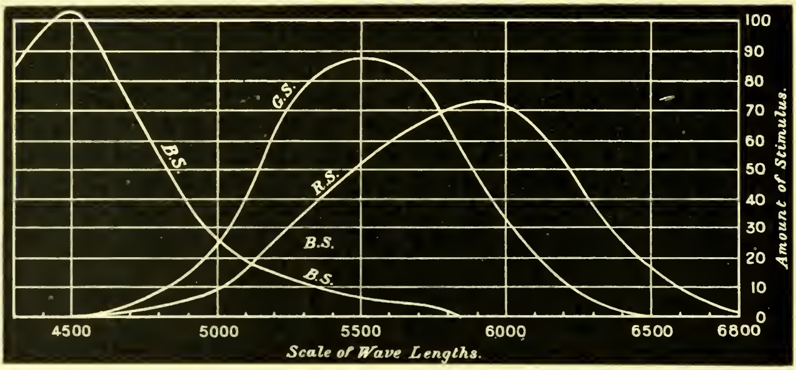


FIG. 85.—(Normal spectrum) curves of equally stimulated red, green, and blue sensations to form the white of the arc light with sloping carbons.

TABLE XLII.—*Normal Spectrum.*

Wave-length.	Spectrum Luminosity.	Percentage Composition.			Luminosity.				
		RS.	GS.	BS.	RS.	GS.	BS.	GS. × 2·38.	BS. × 155.
6800	1	100	...	...	1	...	...	...	...
6700	6	100	...	...	6	...	...	...	...
6600	10	99·7	·3	...	9·97	·03	...	·07	...
6500	17	98·5	1·5	...	16·74	·26	...	·6	...
6400	26	97	·3	...	25·22	·78	...	1·9	...
6300	41	95	·5	...	38·95	2·05	...	4·9	...
6200	59	92	8	...	54·28	4·72	...	11·2	...
6100	75	88·5	11·5	...	66·25	8·75	...	20·8	...
6000	85	84	16	...	71·4	13·6	...	32·4	...
5900	93	78·5	21·5	...	72·93	20·7	...	48·7	...
5800	99	72	28	...	71·28	27·72	...	66	...
5700	100	65·7	34·3	·022	65·7	34·3	·022	81·6	3·4
5600	95	62	38·5	·031	58·9	36·6	·029	87·1	4·5
5500	89	58·5	41·5	·041	52·06	36·93	·036	87·9	5·6
5400	80	55·5	44·5	·058	44·4	35·6	·046	84·7	7·1
5300	70	52·3	47·2	·1	36·61	33·04	·07	78·6	10·9
5200	54	49·3	50·5	·185	26·62	27·27	·1	64·1	15·5
5100	30	46·5	53·1	·4	13·95	15·93	·12	37·8	18·6
5000	18	43·8	55·3	·86	7·88	9·95	·155	23·7	24
4900	11	42	56	2	4·62	6·16	·22	14·7	34·1
4800	7·5	43	52·4	4·6	3·23	3·93	·345	9·4	33·5
4700	5	50	41·3	8·7	2·5	2·06	·435	4·9	67·4
4600	3·5	62	21·8	16·2	2·17	·76	·567	1·8	82·9
4500	2·7	72	7·3	21·7	1·94	·2	·586	·5	90·8
4400	2·1	72	2·2	25·8	1·51	·05	·542	·1	86·6
4300	1·7	72	...	28	1·22	...	·476	...	75·8
4200	1·3	72	...	28	·94	...	·367	...	56·9
4100	1	72	...	28	·72	...	·28	...	43·4
4000	·75	72	...	28	·54	...	·21	...	32·5
3900	·5	72	...	28	·27	...	·14	...	21·7
3800	·25	72	...	28	·13	...	·07	...	10·8

are wave-lengths. The luminosity curve [1] of the normal spectrum is given; knowing the percentage composition in sensations of the different wave-lengths (λ), the sensation curves for the normal luminosity curve is readily obtained by multiplying the luminosity by the percentages and dividing by 100.

[1] Taken with a grating ruled on flat glass. The ruled surface was silvered, and *the silvered surface* was used to form the spectrum.

CHAPTER XVI

COLOUR SENSATIONS IN COLOUR DISCS

Having found the colour sensations for the spectrum, we are now in a position to utilise them in the determination of the colour sensations stimulated by pigments. In Chapter XI. we have shown how three standard pigmented surfaces of red, green, and blue can be used for the determination of the luminosities of other pigments when the colour discs are brought into requisition. It is possible now to extend the usefulness of the standard pigments in the directions of detecting colour blindness quantitatively, and also for ascertaining the proper colour screens to be employed in colour photography. It must be premised that transparent coloured media can be examined in exactly the same way as the pigments are examined.

The first step to take is to get the percentage absorption of the coloured bodies, whether transparent or opaque. The method of doing this has been described in Chapter XI., and need not be repeated. Having obtained the percentage absorption, the next step is to connect these results with luminosities. The luminosities depend on the luminosity curve of the white light employed to form the spectrum and with which the colours are also illuminated.

Having found the luminosity curve of the white, the percentage of absorption is multiplied by the luminosity of the spectrum, and this gives the luminosity curve of the transparent coloured body, or of the pigment. The

luminosity at any point of the curve, when multiplied by the percentage composition of the colour at that point, will give the sensation luminosities of the pigment (or transparent body). (We can also get the colour sensations evoked by the one or the other by multiplying the luminosity of the different sensations at any part of the spectrum by the percentage absorption. We then get the luminosity curves in terms of the sensations.) By calculating from the colour equation to the white, the proportion of the three sensations required to form it, we can readily obtain the amount of white which exists in the pigment (or transparent body). This is most readily accomplished by multiplying the green and the blue sensation ordinates by the factors which, in the naked spectrum, give equal areas. The smallest of the resulting areas is deducted from the other two, and after reconverting into ordinary luminosities there will only be two sensations remaining and white. This will perhaps be more easily understood by working out an example. We give in detail the measures and calculated sensation luminosities for an emerald green, in the light of the arc (sloping carbons).

The equation to the light of the naked spectrum in luminosities is—

$$\overset{\text{RS.}}{68{\cdot}4} + \overset{\text{GS.}}{31} + \overset{\text{BS.}}{{\cdot}58}$$

To make equal areas to show equal stimulation to form white, we have to multiply the GS. by 2·2 and the BS. by 117. So (see Table XLIII.) we have to multiply 141 by 2·2, which is 311·6, and 1·4154 by 117, which is 165, whilst the RS. is 211·4. This makes BS. the smallest area. Deducting this from the (equal stimulation) GS., and dividing by 2·2, we get GS. 66·3, and white 241·7.

TABLE XLIII.—*Colour Sensations of Emerald Green in an Arc Spectrum.*

SSN.	Absorption Percentage.	Luminosity.	Luminosities.		
			RS.	GS.	BS.
62	3	·02	·02	...	...
60	5	·05	·05	...	...
58	7·7	1·5	1·57	·015	...
56	10·5	5·2	5·02	·23	...
54	14	9·8	8·88	·92	...
52	20·5	15·5	13·06	2·46	...
50	24·5	23·6	17·73	5·90	...
48	33·5	33·4	22·48	10·92	·0067
46	43·5	41·3	25·75	15·52	·0128
44	57	48·7	28·38	20·35	·0204
42	67	49·2	26·80	22·44	·0330
40	72·5	40·6	21·02	19·57	·0475
38	76	30·8	15·05	15·73	·0708
36	78	21·2	9·83	11·38	·0897
34	78	12·3	5·40	6·90	·1076
32	75	6·8	2·82	3·75	·1140
30	69	4·3	1·79	2·34	·1335
28	60	2·8	1·24	1·41	·1452
26	51	1·9	·90	·84	·1550
24	41·5	1·1	·66	·31	·1502
22	33·7	·7	·47	·12	·1157
20	25·5	·43	·31	·03	·0957
18	19	·29	·21	·01	·0674
16	11	·14	·10	...	·0363
14	8	·03	·02	...	·0090
12	1	·01	·007	...	·0027
10	...	...			
			Area 211·4	Area 141·0	Area 1·4154

The equation to the emerald green thus becomes—

$$\overset{\text{RS.}}{45{\cdot}8} + \overset{\text{GS.}}{66{\cdot}3} + \overset{\text{White.}}{241{\cdot}7}$$

The luminosity of the pigment is $\frac{353}{865} = 40{\cdot}8$ (865 is the area of the naked spectrum luminosity).

The equation in percentages of this luminosity is—

$$\begin{array}{ccc} \text{RS.} & \text{GS.} & \text{White.} \\ 5{\cdot}34 + & 7{\cdot}64 + & 27 \end{array}$$

It may be of interest to show that the equation to emerald green varies according to the light it is viewed in. In the next table is given the same emerald green when viewed in the light of a paraffin lamp. The percentage of intensity of light after absorption is, of course, the same as in the last case, but the luminosity is different.

TABLE XLIV.—*Emerald Green in Light of a Paraffin Lamp.*

SSN.	Luminosity of Paraffin Light Spectrum.	Intensity.	Luminosity.	RS.	GS.	BS.
62	3·4	3	·1	·1	...	...
60	11·3	5	·6	·56	...	...
58	81·3	7·7	2·6	2·38	·25	...
56	65	10·5	6·8	6·52	·31	...
54	95·7	14	13·5	12·48	1	...
52	100	20·5	20·5	17·26	3·24	...
50	89·2	24·5	21·8	16·39	5·4	...
48	69·4	33·5	23·6	15·61	7·98	·0047
46	52·7	43·5	22·8	14·26	8·53	·0070
44	39	57	21·7	12·94	8·72	·0091
42	28·1	67	18·8	10·45	8·34	·0126
40	20	72·5	14·5	7·47	6·96	·0170
38	13·2	76	10	4·86	5·12	·0230
36	8	78	6·2	2·89	3 28	·0257
34	4·2	78	3·2	1·37	1·81	·0281
32	2·2	75	1·63	·7	·9	·0277
30	1·32	69	·88	·38	·47	·0290
28	·84	60	·49	·22	·25	·0270
26	·52	51	·25	·13	·1	·0230
24	·35	41·5	·14	·08	·04	·0192
22	·22	33·7	·07	·05	·01	·0132
20	·15	25·5	·02	·02	...	·0080
	696			127·12	62·71	·2743

From the equation to the paraffin light it is found we have to multiply the GS. and the BS. by 3·4 and 550 respectively, to make all the areas equal. We then have—

RS.	GS.	BS.
127·2	213·8	151

Here we have to deduct the *red*, 127; and as a result we get—

$$\overset{\text{GS.}}{\frac{86{\cdot}6}{34}} = \overset{\text{GS.}}{25{\cdot}3} \text{ and } \overset{\text{BS.}}{\frac{24}{550}} = \overset{\text{BS.}}{{\cdot}044}$$

and the equation is—

$$\overset{\text{GS.}}{25{\cdot}3} + \overset{\text{BS.}}{{\cdot}044} + \overset{\text{White.}}{164{\cdot}7}$$

The luminosity is $\frac{190}{696} \times 100 = 27{\cdot}3$.

The equation becomes, in terms of the emerald green luminosity,—

$$\overset{\text{GS.}}{4{\cdot}16} + \overset{\text{BS.}}{{\cdot}006} + \overset{\text{White.}}{23{\cdot}14}.$$

It will be noted that with the arc light the emerald green reflected RS. and GS. and white, whilst here the RS. disappears and BS. appears in its place. The luminosity also is altered with the paraffin light; it is 27·3 (696, being the area of the paraffin light spectrum), with the arc light 40·8. The reason obviously being that the paraffin light contains very much smaller luminosity in green rays than the arc light.

The sensation curves of two other pigments have also been calculated out for the arc light and paraffin. The percentage of reflection for these and some others is

given. If the details are required, the sensation curves can be found by multiplying these percentages by the sensation luminosities of the naked light.

The equation for the vermilion as viewed in the arc light was found to be—

$$\begin{array}{ccc} \text{RS.} & \text{GS.} & \text{White.} \\ 142 \cdot 5 & + 16 \cdot 5 & + 5 \cdot 3 \end{array}$$

or, in percentage of luminosity,—

$$\begin{array}{ccc} \text{RS.} & \text{GS.} & \text{White.} \\ 16 \cdot 5 & + 1 \cdot 9 & + 6 \cdot 1 \end{array}$$

the luminosity being 24·5 per cent. of a white surface illuminated by the arc light.

With the paraffin light the equation was—

$$\begin{array}{ccc} \text{RS.} & \text{GS.} & \text{White.} \\ 194 & + 15 \cdot 3 & + 37 \end{array}$$

or, in percentage of luminosity,—

$$\begin{array}{ccc} \text{RS.} & \text{GS.} & \text{White.} \\ 39 \cdot 6 & + 3 \cdot 1 & + 7 \cdot 5 \end{array}$$

the luminosity being 50 nearly.

Here we see that the extra red in the paraffin light gives the vermilion increased luminosity.

The equation for French ultramarine blue, when viewed in the arc (crater) light, is—

$$\begin{array}{ccc} \text{RS.} & \text{BS.} & \text{White.} \\ 2 \cdot 32 & + 1 \cdot 56 & + 34 \cdot 2 \end{array}$$

or, in percentage of luminosity of a white surface,—

$$\begin{array}{ccc} \text{RS.} & \text{BS.} & \text{White.} \\ \cdot 27 & + \cdot 18 & + 3 \cdot 95 \end{array}$$

and it has a luminosity of 4·4 per cent. of white.

In the paraffin light it has an equation of—

GS.	BS.	White.
·6 +	·2 +	15·64

or, in percentage of the ultramarine luminosity,—

GS.	BS.	White.
·012 +	·004 +	3·2

as it has a luminosity of only 3·2 per cent. of a white surface.

CHAPTER XVII

CHANGE IN HUE OF COLOURS BY THE ADDITION OF WHITE LIGHT, AND THE AMOUNT OF COLOUR WHICH WOULD BE ADDED TO WHITE WITHOUT BEING PERCEIVED[1]

When a spectrum is placed upon a screen and a patch of white light is caused to travel along it, more particularly if the white light of the arc crater be confined to one-half of the breadth of the spectrum, it will be at once apparent that there is a change in the hue of the colour. In the red the colour becomes pinker as more of the white light is added, the scarlet becomes orange, the orange yellow, and the yellow green. The yellow-green does not suffer a change, but as the green is approached it becomes yellower in hue, and as the white light passes over the green, this same tendency to yellowness appears. In the blue there is not much alteration, but as the violet is approached a very small quantity of white will make it appear nearly salmon-coloured. If the white light added be that of a paraffin lamp, the red became more orange, the scarlet, as before, orange, the orange the colour of the white light. Where the *hue* of the added white was the same as that of the colour—that is, when the colour was nearly that of the D light—no change took place. The behaviour of the green was as before, as also of the blue; the violet became more yellow-pink than with the arc light. This change of colour, as far as the writer knows, had not been investigated quantitatively; but when the

[1] See Paper No. 25.

investigation had been concluded, it explained several phenomena which had been met with. The value of the change of hue was ascertained in quite a simple manner.

The apparatus employed was the double spectrum apparatus described in Chapter IV., p. 44. In this investigation the lowest half of the beam coming through the prisms was deflected at right angles to the axis of the beam by a right-angled prism, and again deflected by a second mirror nearly parallel to its original direction ; see p. 45.

The two spectra were of approximately the same intensity. Two colour patches could now be formed side by side on a white surface when slits were inserted in each spectrum. The beam of white light reflected from the first surface of the first prism could be thrown on either of the patches. In the investigations here given the white light was thrown on the right-hand patch, which was produced by the spectrum formed from the diverted beam.

The two colour patches overlapped each other, but the two coloured surfaces were caused to touch each other by inserting a rod in the path of the beams. Another rod also cast a shadow from the white light, so that the left-hand patch was free from any mixture of white. Both spectra were accurately scaled, so that the wave-lengths in both were known, and the same colour could be placed in each patch. [The patches of light were about $1\frac{1}{4}$ ins. square.] A qualitative examination of the patches to which white light had been added was first undertaken. The luminosity of the white light was made of about half the luminosity of the D light of the diverted spectrum, so that the red and parts of the green had, of course, a larger percentage

of white added to them than had the yellow, the yellow-green, and the orange.

Two patches of the same red were matched in intensity, and to the right-hand one white was gradually added. It was seen that the hue was changed, and that the mixed light was certainly yellower than the original colour. When the patches were orange, the colour became decidedly yellow, and this change in hue continued until Scale No. 48·7 (λ 5772) was reached, when no change in hue could be noticed.

Passing the slits into the yellow-green, the colour lost much of its green, and when full green was under examination the green became a yellow-green. All through the green part of the spectrum this yellowing was apparent, and in the blue-green, as far as Scale No. 36 (λ 5085), the colour appeared to shift in hue towards the yellow. In the true blue-green, about Scale No. 31 (λ 4886), the addition seemed to make no difference in hue, simply making it appear rather paler. At Scale No. 28 (λ 4776) the mixture of colour and white made the blue become redder. In the violet, the addition of white caused the colour to become redder.

These changes were interesting as throwing light on several discrepancies which have been observed in colour descriptions. It seemed possible that the change in hue from near the red to the blue-green might possibly be measured. Practically this would include by far the most luminous portion of the spectrum.

A patch of green light at about Scale No. 40 (λ 5270) was first examined, and different percentages of white were added to it. With the addition of 50 per cent. of the luminosity of the white (D being 100), it was found that an exact match in hue could be obtained by altering the colour coming through the slit of the other

spectrum, and that a match in luminosity could be obtained by altering the width of the slit. The match made indicated a hue approaching the yellow. As less and less white was added, the match gradually approached the scale number of the undiluted colour.

A series of colours between Scale Nos. 59·5 (λ 6780) and 36 (λ 5085) were examined, with the result which is shown in the annexed table.

It now remained to ascertain if there was any law which could be applied to foretell the change in hue. The first point that was evident was that the Scale No. 48·7 (λ 5772) had something to say to any law. At this point it is to be remembered the addition of white made no alteration in the hue of the colour. On examining Table XXXVIII., p. 239, it was at once seen that at that point of the spectrum the proportions of red to green were exactly those of the proportions existing in white light.[1] This seemed to give a clue to the change in hue that takes place.

It seemed probable that the change in hue in the region of the spectrum under investigation might be due to the addition of the red and green sensation luminosities contained in the white.

To make this hypothesis and its results plain, a reference to Table XXXVIII. should be made, in which columns XIII., XIV., and XV. give the *percentage composition* of the colours in terms of the red (RS.), green (GS.), and blue (BS.) sensations.

In making tests as to the truth of the hypothesis, the proportion of RS. to GS. in white was taken as 69 to 31, the equation for white being—

$$\overset{\text{RS.}}{69{\cdot}4} + \overset{\text{GS.}}{30{\cdot}2} + \overset{\text{BS.}}{{\cdot}4}.$$

[1] As before stated, Scale No. 48·7 is the place where the red and green curves of equal stimulation of the three sensations cut one another.

In one set of observations the value of the full white used was 0·6 the luminosity of D, which gave the proportion of 41·4 RS. to 18·6 GS. A rotating sector was used to get other percentages of white.

The following is a specimen of the calculations made for one colour with different mixtures of white :—

Scale No. 46·23 (λ 5611).

	RS. GS.
The proportion of RS. to GS. *in luminosities* in Scale No. 46·23 is	55·45 + 32·60
Addition of 60 W.	41·40 + 18·60
Total of RS. and GS. is	96·85 + 51·20

Converting this total into percentages, we get—

Scale No. 46·23 + 60 W. . . . . = 65·43 + 34·57

Turning to Table XXXVIII., columns XIII. and XIV., we find that this would give the colour at Scale No. 47·3. It will be seen that this is the same colour that matched the mixture.

Taking half the white (*i.e.* 30 white), we get by the same method of calculation a scale number whose percentage is 64·5 + 35·5. This gives a colour whose scale number is 46·92. It will be seen that the colour matched 46·89.

Again, using one-quarter white (*i.e.* 15 white), we get a percentage equation—

RS. GS.
63·1 + 36·9

which is the proportion of RS. to GS. in Scale No. 46·33 (λ 5618).

The match found was 46·3.

For all the other scale numbers mixed with different proportions of white, the calculations were made in the

same way, and the table attached shows the results of the matches and calculations.

TABLE XLV.

Scale No.	60 W.		30 W.		15 W.		7·5 W.		3·75 W.		1·87 W.	
	Calc.	Found.	Calc.	Found.	Calc.	Found.	Calc.	Found.	Calc.	Found.	Calc.	Found.
56	...	...	...	...	53·6	53·9	54·6	54·3	55·2	54·9	...	...
54·45	...	...	52·19	52·6	53	53·15	54	54	...	...	...	...
50·6	...	...	50·13	50·12	...	...	...	...	...	...	...	...
52·9	...	...	51·7	51·6	52·3	52·2	52·7	52·7	...	...	...	...
46·23	47·3	47·3	46·92	46·89	46·33	46·3	...	...	...	...	...	...
43·65	46·17	46·3	45	45	44·6	44·68	44·14	44·05	...	...	...	...
41·1	...	...	44·5	44·75	43·2	43	42	42·3	41·7	41·43	...	...
38·5	...	...	...	...	41·6	41·6	40·3	40·4	39·5	39·3	...	...
35·92	...	...	...	...	...	...	40·1	40·2	38·5	38·57	37·4	37·3

Another set of matches and calculated values will be found in Table XLVI.

TABLE XLVI.

Scale No.	No W.	43 W.		21·5 W.		10·75 W.		5·37 W.		2·68 W.	
		Calc.	Found.	Calc.	Found.	Calc.	Found.	Calc.	Found.	Calc.	Found.
57·47	57·47	...	...	...	...	...	...	55·96	55·06	55·92	56·49
55·1	55·1	51·76	51·82	52·8	52·8	53·1	53·5	54·1	54·2	54·47	54·9
49·7	49·7	49·34	49·34	49·6	49·5	...	...	...	...	...	...
47	47	47·58	47·6	47·4	47·4	...	...	...	...	...	...
44·3	44·3	46·2	46·16	45·6	45·4	45·14	45·16	44·9	44·83	...	...
41·5	41·5	45·36	45·36	44·1	44	43·1	43	42·35	42·45	...	...
38·2	38·2	44·8	44·83	42·9	42·93	41·27	41·36	40·37	40·33	...	...
36·1	36·1	45·2	44·8	43·2	43·2	41	41·1	39·3	39·5	...	...

The results are shown graphically in the figure.

[In the above tables where there are no results given for the greater proportions of white (as in Table XLV. for Scale No. 56), the match became uncertain owing to too great a proportion of white being added.]

The results show that in the parts of the spectrum under measurement the value of the blue sensation is

unimportant as regards hue, when matches of impure with pure colours have to be made. It is also worthy of remark that there is a considerable range of spectrum colours which can, by adding different proportions of white, be caused to match in hue a pure colour. [This points to using a spectrum in a room free from all white

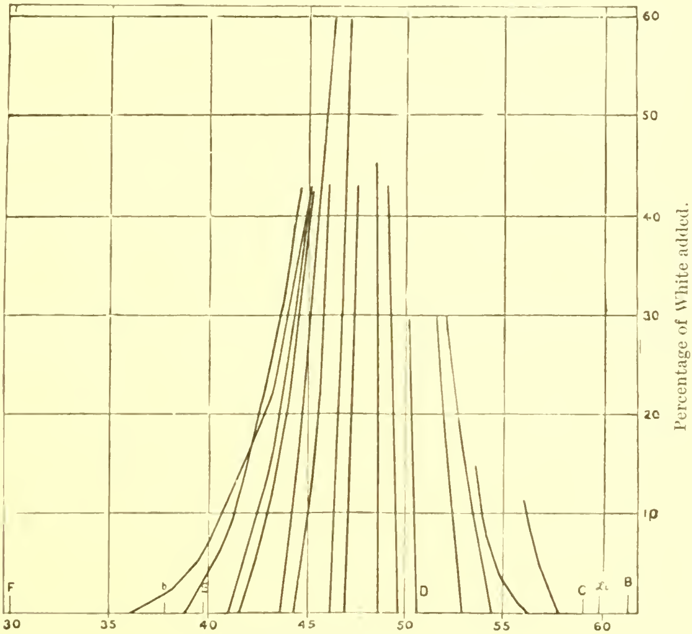


FIG. 86.

light, and with prisms as free from dirt as possible, to prevent the white illumination of the surfaces.]

Another useful fact is this, that if SN. 48·7 (λ 5772) be matched by a mixture of red (say, at the red lithium line) and any green, the amount of green sensation in the green employed can be easily calculated, as the blue has no effect on the match of hue. For although the

colour to be matched may contain blue as well as green sensations, yet the former is accounted for in the white (see Table XXXIX., column V.). [It must be remembered that SN. 48·7 is very readily fixed, from the fact that it is the colour which, with pure blue, can make a white to match the white of the crater of the electric light, quite regardless of the yellow-spot difficulties.]

In the determination of the equations to the three colour sensations, one of the first researches was to find the amount of inherent white in that colour which represented the colour of the green sensation mixed only with the white. When that was found, the equation to make white in terms of the red, green, and blue sensations became an easy matter, and therefrom the amount of red and green sensations was easily calculated.

In some experiments, made with the object of checking the amounts of red and green sensations in the colours (see Table XXXVIII.) lying between SSN.'s 48 (λ 5720) and 36 (λ 5085), the place of the colour to be matched was close to 48·7 and had 69·86 RS. and 30·14 GS. This colour was isolated from one spectrum and matches made with the colours coming through two slits placed in the other spectrum. One of these slits was placed at the position of the red lithium line and the other moved about in the green as required. The matches were made by opening or closing the slits. The following are specimens of the results.

The red slit was placed at SSN. 59·8 (λ 6501), and the green slit at SSN. 40·8. The respective relative luminosities through equal slits were 8·4 and 55 ; the red slit had an aperture of 102 on an empyric scale and the green 27.

The relative luminosities are therefore $102 \times 8{\cdot}4 = 85{\cdot}7$

and $27 \times 55 = 148{\cdot}5$. The two luminosities added together $= 234{\cdot}2$.

As SSN. 48·7 contains 69·86 of RS., 234·2 has to be multiplied by this, the result being divided by 100, which equals 163·6 of RS. (supposing, as shown before, that BS. is negligible). But there is 85·7 of RS. from the red slit. Therefore in the green colour SSN. 40·8 there can only be 77·9 RS., the remainder of the colour being 70·6 GS.

We therefore have the colour SSN. 40·8 represented by—

$$\overset{\text{RS.}}{77{\cdot}9} + \overset{\text{GS.}}{70{\cdot}6} \text{ or } \overset{\text{RS.}}{52{\cdot}5} + \overset{\text{GS.}}{47{\cdot}5}$$

Turning to Table XXXVIII., columns IV. and V., we find that by other means SSN. 40·8 was found to contain 53 RS. + 47 GS.

Similarly, when the green slit was placed at SSN. 43·7, which has a luminosity of 73·1 on the same scale and a width of 27, and the red slit a width of 94, by making similar calculations the colour (43·7) is represented from these observations by—

$$\overset{\text{RS.}}{57{\cdot}7} + \overset{\text{GS.}}{42{\cdot}3}$$

which is the same composition as that found from the table.

Again, with the green slit placed at SSN. 38, the luminosity of which is 36, a match was made when this slit had a width of 34 and the red slit of 102. The resulting calculations gave—

$$\overset{\text{RS.}}{49} + \overset{\text{GS.}}{51}$$

In the table it is 48·65 RS. + 51·1 GS. The part of the spectrum from SSN. 64 (λ 7220) to SSN. 48 (λ 4720)

is readily obtained by ordinary methods, as is the portion from SSN. 36 (λ 5085) to the extreme violet. The most difficult portion is from SSN. 48 (λ 4720) to SSN. 36 (λ 5085), and this can be checked by the method indicated above.

When the white added was that of a paraffin lamp, similar results were obtained, using the proportion in luminosities of red to green in the white as 76 to 24.

There is no difficulty in matching one hue with another when the two are separated by a small dark interval. The eye instinctively ignores the blue present in a rather remarkable manner. We shall find these results have to be considered when considering certain matches which are described in Chapters XXII. and XXV.

We have one or two other questions to answer as to the effect of the addition of white light to a colour. One is, How much spectrum colour can be added to white light without being perceived? Perhaps one of the easiest methods of showing that an appreciable quantity of colour may be added to white without being recognised is by means of a rotating disc of white, 4 to 5 in. radius, on which equal spots $\frac{1}{8}$ in. of the colour under investigation are fastened along a radius with intervals of, say, $\frac{3}{4}$ in. between them, we shall find that the outside rings which should be formed on rotation are invisible, and that it is only the inside spots which form a slightly coloured ring. The reverse may also be observed if the large disc be coloured and the spots are white. It will be found that there is a marked difference in the results.

Using the colour patch apparatus and placing a diaphragm to cover the outside face of the prism, and having a slit in the focused spectrum, we have the means

of placing a coloured spot on the square face of the cube. The spot can then be "drowned" with white light from the reflected white beam. (The brightness of the spot, of course, depends on the width of the slit.) In a set of measurements it was found that the reduced angular apertures of the sector required to drown the colour were as follow for the following Fraunhofer lines :—

Fraunhofer SSN. Lines.	Angle of Aperture.
B	300° *
C	56°
D	14°
E	22°
F	150°
G	2100° *

The large numbers marked with an asterisk were obtained by placing the sector in the white reflected beam. For the other numbers the sectors were in the colours.

Taking the luminosities of the different colours and the luminosity of the white, it was found that between $\frac{1}{64}$ and $\frac{1}{80}$ of the luminosity of the white the colour was unrecognisable.

These results have a bearing on colour equations, and it is only by taking a series of observations that we get a mean equation of sufficient exactitude. The colour equations themselves when a series is taken are proofs of this. The mean of a large number of equations to match white, when the red sensations were all made equal, gave the fact that 1·5 per cent. of green could be added without being perceived. Another series gave 2·5 per cent., another 3·5 per cent., another 2·4 per cent. (Double the differences found were used, since the addition of red might be made instead of green.) The final result was that 2·7 per cent. of green or red might not be perceived when the observer matched white with the rays from the three slits.

Another plan was adopted to compare with the above. It was to see if any change in hue could not be observed, and to find the percentage of sensations which the change indicated. Taking the whole spectrum from SSN. 56 to 29, it was found that an average addition of 2·8 per cent. would escape notice unless very critical examination was made. The greatest addition that could be made without altering the hue was found to be in the green.

CHAPTER XVIII

CONGENITAL COLOUR BLINDNESS

So far we have only considered ordinary or normal colour vision, which is possessed by the large majority of mankind, and it is not a century and a half ago since any suspicion arose that any other kind of vision existed. At that time any departure from the normal vision was a matter of curiosity. In the *Philosophical Transactions of the Royal Society* of 1777, the case of a shoemaker named Harris is described by a Mr. Huddart, who travelled all the way from London to the Midlands in order to see if all the alleged facts regarding him were true. Harris mistook orange for green ; brown he called black ; and he was unable to distinguish between red fruits and the surrounding leaves. This was a case probably of green colour blindness, as we shall see it answers to the more exact methods now extant for diagnosing the kind of defective colour vision.

Dalton's Colour Blindness.

At first colour blindness was called Daltonism (and indeed is still so termed in France), from the fact that the great chemist Dalton suffered from it, and investigated the variation which existed between his and his fellow-creatures' colour sense. It was in 1794 that Dalton described his case. He was quite unaware of his defect till 1792, when he was convinced of its existence from his observation of a pink geranium by candle

light. "The flower," he says, "was pink; but it appeared to me almost an exact sky blue by day. In candle light, however, it was astonishingly changed, not having any blue in it, but being what I call a red colour, which forms a striking contrast to blue." He goes on to say that all his friends except his *brother* said there was not any striking difference in the two colours in the two lights. He then investigated his vision by means of a solar spectrum, and became convinced that instead of normal colour sensations he had only two, at the most three. These were yellow, blue, and perhaps purple. In his yellow he included the red, orange, yellow, and green of others, but his blue and purple coincided with theirs. He says that "part of the image which others call red appears to me little more than a shade or defect of light; after that the orange, yellow, and green seem *one* colour, which descends pretty uniformly from an intense and a rare yellow, making what I should call different shades of yellow. The difference between the green part and the blue part is very striking to my eye; they seem to be strongly contrasted. That between the blue and purple much less so. *The purple appears to be blue much darkened and condensed.*" (These italics are ours.)

In what we have quoted we have a splendid description of a case of complete red blindness, and it has all the advantage of having been made by a great scientific man and observer. It is a model which may serve for less acute observers who are similarly or less deficient in some sensation.

Dalton further said that a florid complexion looked blackish blue on a white ground. (He saw the blue in the blood, and not the red.) A laurel leaf was a good match to a stick of sealing wax. (He only saw the green which was present in both.) Some browns he called red,

and others black. (The red of the spectrum was a shade to him; hence he called such shades red.) By the electric light and lightning, colours appeared as in daylight; whilst in moonlight and candle light the colours changed from what they appeared in daylight, but were alike. (Moonlight is enfeebled sunlight, and the red end of the spectrum is much enfeebled, as is also the blue and the violet.)

Extent of Colour Blindness in the Population.

The percentage of those who do not possess the fully developed normal colour sense is stated from statistics to be between four to five per cent. of the male population, and about the same number per thousand of the female population. It is more than probable that this is an under-statement, as the more delicate tests which are now possible to use give a larger percentage of both men and women who are defective.

Heredity and Colour Blindness.

The colour blindness in a healthy subject is congenital, born with the person, and is very often hereditary. In some cases it has been traced to exist in at least three generations. Referring to the case of Dalton just quoted, it is remarked that his brother agreed with him as to the colours seen. We may presume that Dalton's father was similarly affected. The writer has had several cases of brothers partially colour blind, and it was invariably found that both were deficient in the same colour sense, but sometimes one more so than the other. In one family, of which two members were distinguished physi-

cists, all the brothers and sisters were deficient in one colour sense, but not to the same degree, and from what has been stated to him the writer believes that the father was deficient. Again, the writer knows a case in which the father, though an artist, was colour blind, and the son has the same kind of deficiency in his colour sense. A case quoted further on will show that two brothers who see no colour but light only are alike in this respect, and presumably the defect was inherited.

As we have said before, the colour blindness of this type is congenital. There is another class of colour blindness which is acquired owing to disease or over-smoking, but it carries with it in addition the loss of form—that is, that the sight becomes indistinct. Congenital colour blindness is, so far as known, incurable, whilst that caused by disease may be curable, or can be ameliorated if treated in time.

Colour Blindness unnoticed by the Possessor.

Colour blindness is often unnoticed by its possessor. For instance, one gentleman of the age of seventy-four was completely colour blind to one sensation, and yet during all his years he had never found out that he differed from the majority of persons in his colour sense. His family had suspected that there was something abnormal, owing to mistakes that he had made in recognising different colours. The writer found out what was really wrong by his naming the red velvet seat of a chair as black velvet. When tested in the laboratory, it was found that one of the three colour sensations was absolutely absent. A colour blind person may often be told by incongruities in his or her dress. The clashing of incongruous colours is one sign, though not quite

always a sure one, as it may be a love of eccentricity which induces it.

There have been cases where a person in deep mourning has worn a bright red tie, and when taxed with the society outrage that he had committed contended that it was a black tie. A bright green is sometimes mistaken for white, and the incongruities that can be committed in such a case can be imagined. Pages might be filled of such examples of persons who have never guessed that their colour vision was not normal. It is sufficient to say that the percentage of those who confess to a want of proper colour sense is not large.

Danger of Colour Blindness.

On the railways, in the navy and mercantile marine, colour blindness in a signalman, engine-driver, or look-out man is a danger to the community, since the colour of signals cannot be seen as they ought to be on a railway; and in the marine services neither ship's lights nor flag signals can be correctly stated. That accidents have happened owing to colour blindness of a railwayman or a seaman cannot be doubted, though inquiries as regards collisions have not brought out the facts. Owing to the general ignorance which prevails in all grades of society as to the mistakes that can be made by the colour blind, it is almost unheard of that any witness has been examined as to whether he has normal colour vision before he gives his evidence. The often silly remarks made by the many about colour blindness lead one to regret that children are not taught at school that such a defect of vision may exist, and be harmful to the community in certain walks of life.

The Explanation of Newton's Colours in the Spectrum.

Turning to the colour sensations, we find a ready explanation of the colours which Newton placed in the spectrum. He saw there was a red, orange, yellow, green (blue-green [1]), blue, ultramarine (he called it indigo), and violet, and these may be taken as the general hues seen by a normal eye.

In Table XXXIX., page 242, there are columns giving the composition of the different colours from the red to the violet. It will be seen that there is an unbroken sensation of red from the extreme end of the spectrum to SSN. 57, except a minute trace of green at SSN. 58. At this number the green sensation comes into the colour more and more to SSN. 52. The combination of the more powerful red sensation with the green gives a colour which may be classed as orange. From SSN.'s 52 to 50 the green sensation is still more developed, which gives a yellow. At SSN. 49 a new factor is introduced in the shape of white, and the green sensation becomes predominant to SSN. 38, and the general hue is green. From SSN.'s 38 to 34 a small quantity of blue appears with a diminishing quantity of white, and this causes the blue-green colour. From this number to SSN. 24, only the green and blue sensations with white are extant, and the hue changes to a blue. From SSN.'s 24 to 16, we have red reappearing, and the blue sensation and white are also present. This gives a subdivision, which may be classed as ultramarine, whilst from SSN. 16 to the end of the spectrum we have only the red and blue sensations in the colour, which give rise to the violet or purple.

[1] Blue-green was not in Newton's list, but it is included here, as it is a very definite hue to those possessing normal colour vision.

The following is a table of colours recognised by normal vision when the whole spectrum is viewed. A large number of persons were examined, and the mean beginning and end of the eight colours are given.

TABLE XLVII.

	From Naked Spectrum.			From Diagram.		
	Beginning.		End.	Beginning.		End.
Red . .	End of spectrum	to	55	End of spectrum	to	57
Orange . .	55	,,	51	57	,,	50·5
Yellow . .	51	,,	49	50·5	,,	48·5
Green . .	49	,,	37	48·5	,,	37·5
Blue-green .	37	,,	34	37·5	,,	34·5
Blue . .	34	,,	24	34·5	,,	24
Ultramarine .	24	,,	18	24	,,	16
Violet . .	18	,,	end of spectrum.	16	,,	end of spectrum.

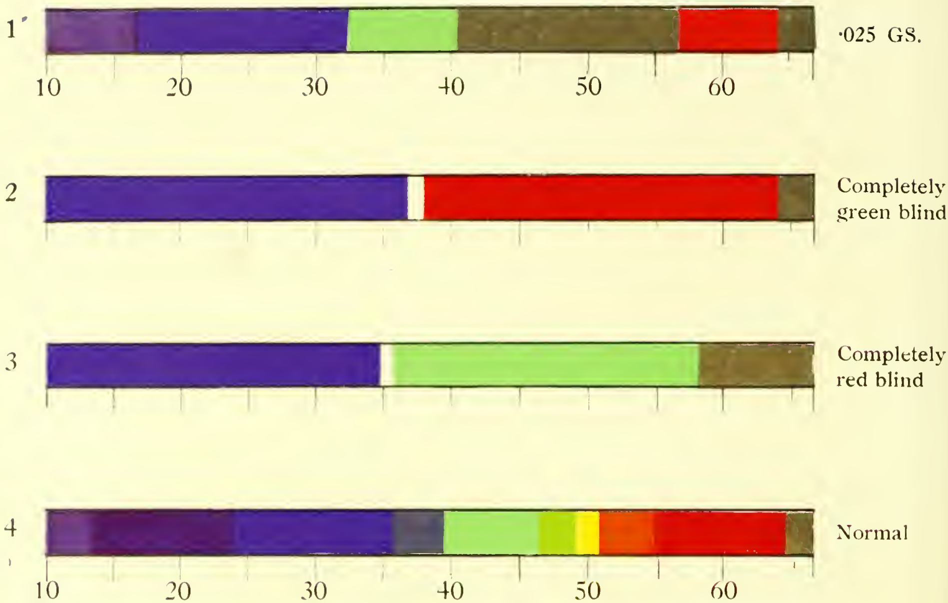
The boundaries of the colours viewed in the naked spectrum are undefined, one colour blending into another; that the similarity of the diagrammatic and observed boundaries are so nearly alike, is somewhat remarkable.

Normal Spectrum Colours as seen by the Colour Blind.

It is interesting to show the colours which to the normal eye represent the white of the colour blind. Let three slits be placed in the spectrum: one at the position of the red lithium line, another at SSN. 37·5 (for the ordinary arc light), and the third at the position of the blue lithium line. Let the normal eye match the white of the arc light with the mixture of the rays coming through the three slits. If now we cover up the red slit, the colour on the screen will be a sea green, and this will match the white of the red blind.

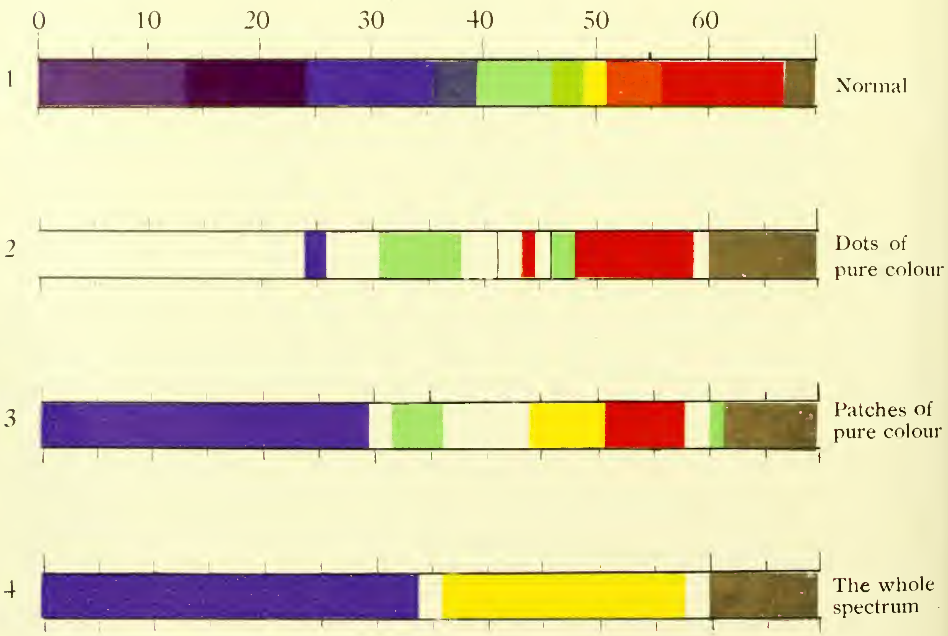
Similarly, covering up the green slit we get a purple which matches the white of the completely green blind. (We can cover up the blue slit and we shall have the white of a blue blind, but as such blindness is almost unknown, it is not necessary to deal further with this form of blindness.) If a person is half red blind, we shall get the colour of his white by closing the red slit to half its aperture, and so with the green blind. For other factors of colour blindness we have to close the slits, multiplying the aperture by the factor. If the colour blindness is incomplete, we may expect that in naming, the colours to the normal eye may differ considerably from those which they appear to the latter. Thus a partially red blind would be apt to class the yellow as greenish and the scarlet as yellow; the extreme end of the red would not be perceived at all, unless the spectrum were very bright; the limits of the green would also vary, and, in bad cases of red deficiency, the violet would become a blue. In cases of partial green blindness, the yellow might be called orange or even red, and the blue-green would be classed as green. In very bad cases of green deficiency, the whole of the spectrum from the yellow to the blue might be called white or grey, as the amount of their white in the intermediate regions would shroud the colours which they could see if deprived of the white. In naming the colours of the spectrum, it must be remembered that names are learnt from the normal eye's perceptions, and it is the endeavour of the colour blind to call the different parts of the spectrum by the appropriate names from recollection of colours which they see in everyday life, and which are named by normal vision. The colour blind's judgment is often formed by the luminosity of a colour, and not by any marked difference

PLATE I.



Spectrum colours as named by persons who were completely or nearly completely red or green blind.

PLATE II.



Spectrum colours as named by a person who possessed ·05 of Red Sensation.

in the hue, as is the case with the normal eye This being the case, we may expect (and our expectations are usually realised) that under varying circumstances the colour blind will give various names to the same (normal) colour.

Plate I. illustrates the colours which persons completely and one nearly completely colour blind name the spectrum colours.

There has been no endeavour in these diagrams to give any idea of the luminosities of the different colours, but only the hues which the colour blind say they see.

Plate I.

In Plate I. the bottom figure shows graphically how the normal eye sees the spectrum.

No. 2 line shows how the completely red blind sees the spectrum.

No. 3 line shows how the completely green blind sees the spectrum.

No. 4 is a case of nearly complete green blindness.

Plate II.

No. 1 line is the normal spectrum shown graphically.

No. 4 shows the naked spectrum colours as described by a person who was largely deficient in red sensation.

In 2 line are the names which he gave to dots of pure spectrum colours about $\frac{3}{16}$ of an inch in diameter when standing about 16 feet away from them.

In 3 line are the names which he gave to individual patches when pure spectrum colours were shown to him.

CHAPTER XIX

COMPLETE RED AND GREEN COLOUR BLINDNESS[1]

It will perhaps be easier for the reader if we describe what has been found to be the deficiencies in perception. Turning to Fig. 98 of the last chapter, we have the three sensations for the normal eye shown in terms of *equal stimulation for the three perceiving apparatus.*

The Normal Sensations which are absent to the Colour Blind.

If one of these sensations is absent, say the red, in the first instance, what effect should it have on the recognition of the different colours of the spectrum?

In the first place, from SSN.'s 60 to 65 there will be no sensation of colour, as in that region only the red should be stimulated, and there is no red apparatus to stimulate. Between SSN.'s 50 to 60 there will only be the green sensation, and that will be felt in a purity that the normal unfatigued eye cannot feel. All the colours from the scarlet to the yellow, to the red blind, will be different intensities of the green sensation.

At SSN. 49 the blue sensation will begin to be felt. Taking a forward step, let us see what the sensation of added blue means to the red blind. At SSN. 34·6 the green and blue curves cut one another; and as the ordinates at the point of intersection are equal, the colour

[1] See Papers Nos. 5 and 6.

which to the normal eye is green will appear to be a white similar in hue to that which forms the spectrum, and can be matched with it by the red blind. The addition of blue from SSN.'s 49 to 34·6 means that the green sensation begins to be slightly paler at 49, and the paleness increases until at 34·6 all the colour has gone. From SSN. 34·6 to SSN. 16 the green sensation diminishes gradually, whilst the blue increases, so that at, say, SSN. 33. there is white, to which a little blue has been added, and the blue increases in purity until SSN. 16 is reached, when there is no admixture of green at all.

Theoretically, then, the absence of the red sensation means that there are only two sensations which in the centre of the spectrum are more or less contaminated with white. If a red blind be asked to name the colours of the spectrum, he will name them as stated above, though he may call the green *yellow*; but this is rarely the case, and has no significance, being merely a question of nomenclature. To the totally red blind person the spectrum is shortened at the red end, and he sees only green, and blue diluted with his white, the white being a mixture in definite proportions of green and blue. If, then, we find anyone who cannot see the red from SSN.'s 60 to 65, we shall diagnose that he is red blind. It must always be difficult for a person with normal vision to interpret the descriptions which colour blind people give of the spectrum.[1] The majority of the persons they associate with have normal vision, and they educate themselves to recognise and name the colours as named by this majority, judging not by the hue, but by the shades and purity of the two sensations they possess. It is this system of self-education that breaks down when

[1] It is less difficult for persons who carry out experiments in colour fatigue of the retina (see Chapter XXV.).

proper tests are applied. The kind of tests which lead to the certainty of the detection of colour blindness will be given later.

When there is complete green blindness, we can ascertain what theoretically would happen when such a colour blind describes the spectrum. In the first place, the spectrum would be of the same length as it is to normal vision. Between SSN.'s 50 and 65 red only would be felt, but in different shades, the maximum brightness being at about SSN. 52. At 49 blue should begin to be felt; and will gradually increase as the normal full green is approached. At 37·5 in the green the two equal area curves cut one another, so at this point of the spectrum he should see a white which would match that of which the spectrum is formed. From this point to SSN. 49 the spectrum colours should be to him red mixed in gradually diminishing quantities with the (green blind) white. On the more refrangible side of 37·5, the (green blind) white would be mixed with violet in gradually increasing quantities till SSN. 14, where the relative amounts of the red and blue sensations remain the same. When a green blind is asked to name the various colours of the spectrum, he may call the red sensation yellow, red, or green, and he may from education even name the various colours correctly, but tests with the spectrum will soon convince the examiner that what he theoretically ought to see he does see, and that the foregoing description is correct.

Reverting to what the green blind calls white, it was shown in the last chapter that his white is a brilliant purple, and yet we have just stated that there is a point in the *green* of the spectrum which to him is a match to the white.

A glance at the diagram, p. 240, will explain this

apparent anomaly. At SSN. 37·5 there is no green sensation as felt by the normal eye, and the only sensations felt by the completely green blind are blue and red, which when mixed give the purple of the experiment described in the last chapter.

Luminosity of the Spectrum to the Colour Blind.

It is quite as easy, indeed it is easier, for the completely colour blind to measure the luminosity of the spectrum than it is for the normal eye, as there are only two sensations instead of three to deal with, and there is one place for each kind where the spectrum matches exactly their white.

In the trichromatic theory of colour vision, the three sensations of red, green, and blue are each totally distinct, and in complete green or red blindness one of these two sensations is totally absent. It therefore follows, if this theory is not merely a working hypothesis, the luminosity curve of the red blind, if added to that of the green blind, when the maximum numbers given in cols. XIII. and XIV., Table XXXVIII. (p. 239), are taken as maxima, should give the luminosity curve of normal colour vision, with one luminosity curve of the blue sensation in addition. For red blind luminosity is composed of green sensation + blue sensation, the green blind luminosity of red sensation + blue sensation, and the normal colour vision curve of all three sensations. By the addition of the red and green blind luminosity curves, we should have that of normal colour vision curve, together with an extra blue sensation. The luminosity of the blue sensation is very small compared with those of the other two, and may vary slightly, as said before, owing to difference in the absorption by the yellow spot,

so that roughly the addition of the red blind and green blind curves should be very close to the curve of normal vision.

TABLE XLVIII.—*Luminosities of three Completely Green Blind and four Completely Red Blind. The Mean Luminosities of the Red and Green Blind are added together and compared with the Luminosity of the Normal Colour Vision, to which an extra Blue Sensation Luminosity is added.*

SSN.	λ.	Green blind.				Red blind.					Addition of IV. and IX.	Luminosity of Normal Colour Vision +BS.
		I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
		E.	F.	D.	Mean.	G.	H.	K.	L.	Mean.		
62	6957	2	2	2	2	...	...	...	...	...	2	2
60	6728	7	7·6	7·2	7·3	...	...	...	...	...	7·3	7
58	6521	20	21·8	22·2	21·3	...	...	...	...	...	21·3	21
56	6330	46	48	46	46·7	3·3	3	2·8	3	3	49·7	50
54	6152	75	71	72·2	72·7	8·1	7·5	7·1	7	7·4	80·1	80
52	5996	80·3	81·6	80·6	80·5	16·6	16·5	13·7	17	15·9	96·4	96
50	5850	75	77	74·4	75·5	27	24	26·2	25	25·5	101	100
48	5720	67	64·8	66·1	66	31·4	30	32	30	30·8	96·8	97
46	5596	56	55·8	55·5	55·7	32·8	32·5	33	33	32·8	88·5	87
44	5481	45	46	45·5	45·5	30·5	32	31·2	32	31·7	77·2	75
42	5373	35·5	35	35·5	35 3	27	28	28·3	28	27·8	63·1	62·5
40	5270	27·1	26·4	26·5	26·7	21·4	24·5	23·3	23	23	49·7	50
38	5172	16·5	18	18	17·5	15·2	17	18·1	17	16·8	34·3	36·1
36	5085	10	11	11·9	10·9	9·5	11·5	12·5	10	10·9	21·8	24·1
34	5002	6·2	6·2	7·2	6·5	6	6·5	6·8	6·8	6·5	13	14·3
32	4924	4·5	3·4	5	4·3	3·8	4	4·4	4·4	3·9	8·2	8·6
30	4848	3·4	2·5	3·6	3·2	2·4	2·8	2·5	3·2	2·7	5·9	5·9
28	4776	3	2	2·8	2·6	2·2	2	2	2·6	2·2	4·8	4·2
26	4707	2·5	1·65	2·1	2·1	1·9	1	1·2	1·9	1·5	3·5	3
24	4630	2	1·30	1·5	1·6	1·4	·7	·8	1	1	2·6	2·2
22	4578	1·7	1	1·2	1·3	1·1	·5	·5	·7	·7	2	1·65
20	4517	1·5	·75	1	1	·8	·3	·3	·3	·4	1·5	1·33

A large number of curves[1] have been plotted by the writer from observations of luminosity made by both

[1] See Paper No. 21.

kinds of complete colour blindness. Luminosity curves are shown in Fig. 87, and the table gives the measures made. In the case of the red blind the maximum of brightness is at about SSN. 46, and the curve of luminosity is made at that point to have an ordinate of 32·8. Similarly, the green blind has a maximum at SSN. 52,

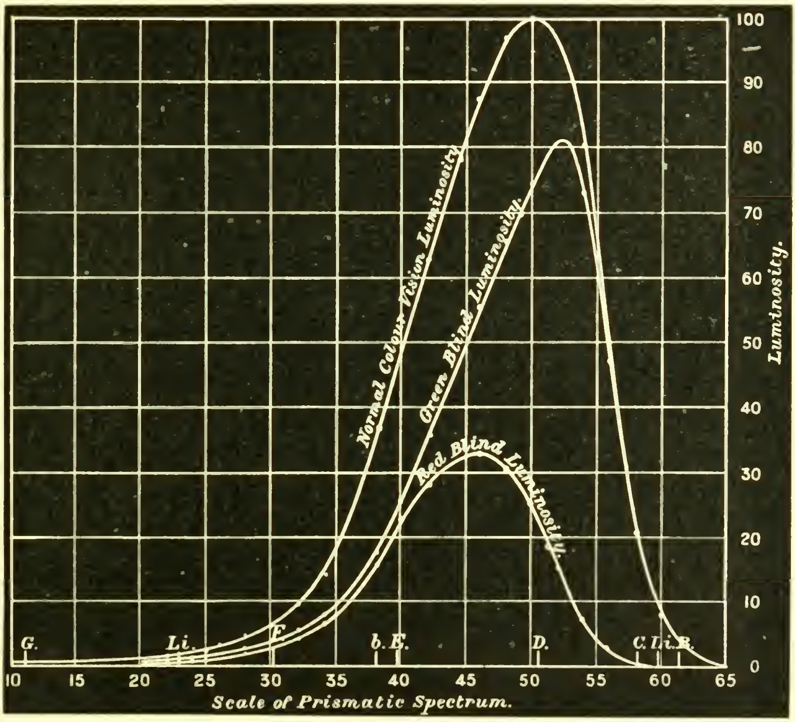


FIG. 87.

and at this point the ordinate is made to have a height of 80·6, whilst the normal vision curve has a maximum near SSN. 50, where it has an ordinate of 100.

These numbers for the maxima of the red and green blind are those found for the red and green sensation in Table XXXVIII. That it is justifiable to use these

numbers will be shown by the red and green blind "extinction of light" curves (see p. 291).

Comparing together columns X. and XI., it will be seen that they agree together, and that any small difference is accounted for by errors of observation of eight persons in all, seven of whom were unacquainted with the method of measuring the luminosity of colour until their luminosity curves were taken.

Details of the Measurements of the Green Sensation Curve by a Red Blind.

We give in some detail the finding of the luminosities of the green sensation existing in the different colours by an observer who was totally red blind.[1]

These observations were the matching in luminosity and "hue" of a patch of white light by a mixture of two colours, one on each side of the "neutral" point. Two standard places in the spectrum were chosen, in each of which was placed a slit—one in the red, in which it was known that the blue sensation was absent, though the green sensation was present, and the other in the violet, in that position in which the green sensation was absent.

The relative luminosities of these two rays when passing through equal apertures of slits was determined by X.: that in the red (SSN. 56·82) being 2, and that in the violet (SSN. 9·11) 0·14. These luminosities, though taken on a different day to those on which the luminosity curves were taken, agree well with the luminosities shown by the curve at these points.

The observations were made as follows. The slits were first of all kept in the standard places, and a series

[1] See Paper No. 26.

of matches made with the white by opening or closing the slits till the right hue was acquired. The luminosity of the white patch, when it matched in luminosity the mixed colours (the two patches being in contact with one another, each being $\frac{3}{4}$ inch square), was measured by introducing into the path of the beam forming it sectors the apertures of which opened and closed at pleasure during rotation. The aperture of the sector indicated the white luminosity. The relative widths of the slits were measured by placing a lens of very short focus in the path of one of the slits. This gave a magnified image of the aperture on a distant screen on which a $\frac{1}{2}$-mm. scale was fastened. When the aperture of one slit was measured, the slide in the spectrum carrying the slits was moved, so that the second slit was illuminated by the same colour and its aperture measured. The slide was then moved back to the position it first occupied, the small lens moved away, and fresh readings were taken. (Care was taken that the small lens always occupied the same place in relation to the first slit when it had to be replaced.) When a series of observations with the slits in the standard positions had been made, the red slit was moved to the sodium D light and a fresh series made with the first slit in that position and the second in the standard position in the violet. A series of readings was made as before. The red slit was then moved into various positions between SSN. 56·8 and the neutral point, the violet slit remained fixed, and matches were made with the white. When this was finished, the red slit was placed at D and matches of white made with the violet slit, when in different parts of the spectrum, on the more refrangible side of the spectrum. (The D light was chosen for the red slit, as it contained a larger

amount of green sensation than the standard position, which was convenient.) Where the width of either or both of the slits was very small, the aperture to be measured was increased by placing in the path of one or both of the rays a small cardboard sector with fixed apertures. After measuring the apertures, they were one or both diminished according to the aperture of the cardboard sector.

The method by which the composition of the different rays was determined is shown below, two examples illustrating it.

The red slit was placed at SSN. 48·8, the violet slit being at the standard place SSN. 9·11.

The equation to match white was, in terms of slit apertures—

$$\text{(i.)} \quad \overset{(48\cdot8).}{41} + \overset{(9\cdot11).}{106} = \overset{\text{White.}}{55}$$

Increasing this equation to make 100 white, we have—

$$\text{(ii.)} \quad \overset{(48\cdot8).}{75} + \overset{(9\cdot11).}{193} = \overset{\text{White.}}{100}$$

The standard equation with SSN.'s 56·82 and 9·11, in terms of slit apertures, had been found to be—

$$\text{(iii.)} \quad \overset{(56\cdot82).}{1116} + \overset{(9\cdot11).}{228} = 100$$

Equating (ii.) and (iii.), we get—

$$\overset{(48\cdot8)}{75} = \overset{(56\cdot82).}{1116} + \overset{(9\cdot11).}{35}$$

Multiplying the right-hand members by 2 and 0·14 respectively, we get, after dividing by 75, the luminosity of SSN. 48·8 as—

$$\overset{\text{GS.}}{29\cdot9} + \overset{\text{BS.}}{0\cdot065}$$

in luminosities (GS. and BS. being used as the symbols of green and blue sensations).

Again, for SSN. 46·23 we have the following equation :—

(46·23).		(9·11).		W.
18	+	46	=	25

or

(46·23).		(9·11).		W.
72	+	184	=	100

Equating this with (iii.) and converting the slit apertures into luminosities, we get—

$$\text{Luminosity of SSN. } 46{\cdot}23 = \overset{\text{GS.}}{31{\cdot}5} + \overset{\text{BS.}}{0{\cdot}085}$$

In this manner the luminosities of the different wave-lengths to X. were worked out.

The following is a table of the final determinations :—

Table XLIX.

SSN.	GS.	BS.	SSN.	GS.	BS.
54·27 =	7·5	+ 0·003	35·62 =	11·2	+ 0·093
50·6 =	22	+ 0·005	30·22 =	4·05	+ 0·155
48·8 [1] =	29·9	+ 0·065	25·01 =	0·77	+ 0·238
46·23 [1] =	31·5	+ 0·085	19·71 =	0·11	+ 0·252
40·92 [1] =	26·5	+ 0·086	14·39 =	0	+ 0·203
38·62 =	19·2	+ 0·068	9·11 =	0	+ 0·14

These figures were plotted and a curve drawn through the points. The following table was then constructed from the curves.

[1] The blue sensation curve is like that of the normal curve as far as 38·62; below that it differs, but the amount of blue is so small in the equation that it may be possibly different when repeated observations are made.

TABLE L.—*Table showing X.'s Sensation Curves as Luminosities; also the same Curves from* Phil. Trans.; *also X.'s Total Luminosity Curve taken direct.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
SSN.	λ.	X.'s sensation curves in luminosities		X.'s GS. + BS. added.	Colour sensation in luminosities from Table XXXVIII.		Normal GS. + BS. added.	X.'s luminosity curve taken direct.
		GS.	BS.		GS.	BS.		
58	6521	1	...	1	·21	...	·21	·2
56	6330	2·5	...	2·5	2·25	...	2·25	2·25
54	6152	7·2	trace	7·2	7·60	...	7·60	7·5
52	5996	15	trace	15	15·36	...	15·36	15·1
50	5850	25	·024	25·02	25	...	25	25
48	5720	31	·062	31·06	31·78	·020	31·80	32
46	5596	32·5	·087	32·59	32·70	·027	32·73	32·5
44	5481	31·5	·100	31·6	31·30	·032	31·33	31·5
42	5373	29·2	·093	29·3	27·75	·042	27·80	27·5
40	5270	25	·080	25·8	24·09	·058	24·15	24
38	5172	18·5	·070	18·57	18·43	·083	18·52	18·5
36	5085	12	·090	12·09	12·83	·101	12·90	13
34	5002	8·3	·110	8·41	7·86	·124	7·98	7·5
32	4924	5·5	·134	5·63	4·77	·145	4·92	4·5
30	4848	3·5	·160	3·66	3·08	·174	3·83	3
28	4776	2·2	·190	2·39	2·03	·202	2·23	2
26	4707	1·2	·220	1·42	1·15	·243	1·39	1·2
24	4639	·5	·250	·75	·53	·262	·79	·95
22	4578	·3	·255	·55	·27	·247	·52	·75
20	4517	·11	·253	·36	·10	·234	·33	·55
18	4459	·04	·242	·28	·04	·202	·24	·42
16	4404	...	·224	·22	·01	·180	·19	·25
14	4349	...	·195	·19	...	·154	·15	·22
12	4296	...	·175	·17	...	·126	·13	·2
10	4245	...	·150	·15	...	·098	·10	·17
8	4198	...	·130	·13	...	·073	·07	·125

Column I. is the Standard Scale No. (SSN.), column II. is λ, columns III. and IV. the green and blue sensation curves derived from X.'s equations, column V. his luminosity curve by the addition of III. and IV., columns VI. and VII. are the curves of the green and blue sensations taken from Table XXXVIII., column VIII. is the luminosity derived from the addition of

VI. and VII., column IX. is X.'s luminosity curve taken direct and reduced as before described.

The results obtained from the measures made by X. are valuable. It has frequently been asserted that when luminosities are measured in the manner described in Chapter VIII., something is measured which is not luminosity. Now X., when he made his colour equations, matched the white with the rays coming through dif-

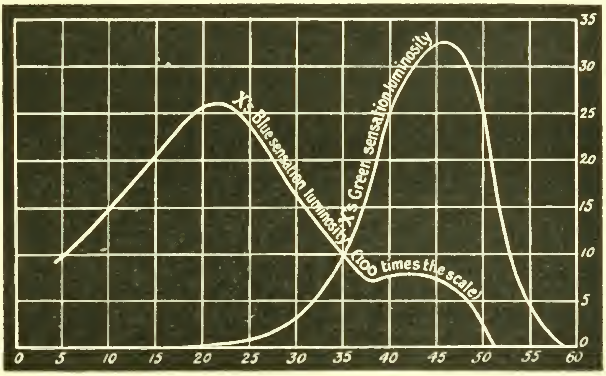


FIG. 88.—X.'s colour curves. (Red blind.)

ferent *apertures of slits*, and the only luminosity he measured was the luminosity of the two white patches, to which no objection can be raised. It was only when these readings had been made that the question of luminosity of his colours entered into the problem. Only two luminosities of coloured rays were measured, and these were applied to his slit apertures to find the luminosity of the different rays. As mentioned before, the luminosity measured direct and that derived from the equations are practically identical, so that a totally different kind of measurement confirms the direct method of measuring the luminosity.

We will now take D.'s luminosity curve and X.'s

green luminosity curve only, which should give, when added together, the normal colour vision curve closely, as only one blue sensation curve will be found in the compounded curve. Table LI. gives the results. The comparison of the compounded curve with that taken direct by the normal colour vision eye shows how closely they are alike, and the similarity is very remarkable, considering that the observations of three different persons are used.

TABLE LI.

I.	II.	III.	IV.	V.	VI.
SSN.	λ.	D.'s luminosity.	X.'s green sensation luminosity.	III. and IV. added.	Normal luminosity.
62	6957	2	...	2	2
60	6728	7·2	...	7·2	7
58	6521	22·2	1	23·2	21
56	6330	46	2·5	48·5	50
54	6152	72·2	7·2	79·4	80
52	5996	80·6	15	96·1	96
50	5850	74·4	25	99·4	100
48	5720	66·1	31	97·1	97
46	5596	55·5	32·5	88	87
44	5481	45·5	31·5	77	75
42	5373	35·5	29·2	64·7	62·5
40	5270	26·5	25	51·5	50
38	5172	18	18·5	36·5	36
36	5085	11·9	12	23·9	24
34	5002	7·2	8·3	15·5	14·2
32	4924	5	5·5	10·5	8·5
30	4848	3·6	3·5	7·1	5·7
28	4776	2·8	2·2	5	4
26	4707	2·1	1·2	3·3	2 8
24	4630	1·5	·5	2	1·9
22	4578	1·2	·3	1·5	1·4
20	4517	1·03	·11	1·14	1·1
18	4459	·72	·04	·76	·86
16	4404	·62	...	·62	·7
14	4349	·52	...	·52	·56
12	4296	·42	...	·43	·45
10	4245	·34	...	·34	·34

In the table, column I. is the SSN., column II. the wave-length, column III. shows D.'s luminosity curve, column IV. is the green sensation of X. in luminosity, column V. gives the results of the addition of D.'s luminosity to X.'s, whilst column VI. shows the luminosity curve for normal colour vision. Columns V. and VI. have to be compared together to test the strength of the theory.

Extinction of Light by the Completely Red and Green Blind.

The extinction of light from the spectrum colours[1] by completely red and green blind eyes to obtain measures of the total quantity of light which they see compared with an eye having normal vision now becomes necessary. By such measures we ought to confirm the maximum luminosity of the spectrum to the completely red and green blind relatively to the normal as shown in the sensation curves at p. 239. The table gives a specimen of the extinction of light in millionths of the luminosity when the D light has a luminosity of 1 candle at 1 foot to normal vision. In both examples the maximum ordinates in the luminosity curves of the green and red blind have been made 80·6 and 33 respectively. If under these conditions the extinction of the blue end of the spectrum is the same for the green blind and normal, since they both have sensations of red and blue in that region, and if the red blind shows a proper ratio for his extinction values in the same region compared with the normal, we have the strongest evidence that these values for the maxima of the two kinds of the complete colour blinds are correct.

[1] See Papers Nos. 4 and 21.

TABLE LII.—*Extinction of different Colours of the Spectrum by a Green blind and Red blind.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
		Green blind.			Red blind.			
SSN.	λ.	Extinction when D=1 candle at 1 foot (to Normal Vision) in millionths of Original Luminosity.	Measured Luminosity of spectrum to Green blind.	Extinction when every ray is 1 candle.	Extinction when D=1 candle at 1 foot (to Normal Vision) in millionths of Original Luminosity.	Measured Luminosity of spectrum to Red blind.	Extinction when every ray is 1 candle.	Extinction when every ray is 1 candle to normal eye. *See* Table XVII.
60	6728	1200	7·2	...	...	...	...	262·5
58	6521	550	22·2	122	...	...	...	220·5
56	6330	260	46	119·6	770	2·5	192	190
54	6152	150	72·2	75·8	250	7·6	190	156
52	5996	65	80·6	52·3	90	16·6	149	93
50	5850	25	74·4	18·6	27	27·1	72·7	35
48	5720	12·5	66·1	8·26	15	31·4	47·1	16·5
46	5596	7·5	55·5	4·16	10	32·8	32·8	8·87
44	5481	5·5	45·5	2·5	7	30·5	21·35	5·55
42	5373	5	35·5	1·77	5·5	27	14·8	4·09
40	5270	5	5	1·32	5	21·4	10·7	3·27
38	5172	5	18	·9	5	15·2	7 6	2·46
36	5085	6	11·9	·71	6	9·5	5·7	1·82
34	5002	7	7·23	·5	7	6	4·2	1·25
32	4924	9	5·05	·45	9	3·8	3·42	·99
30	4848	12·5	3·61	·45	11	3	3·3	·9
28	4776	17	2·79	·476	14·5	2·3	3·48	1·04
26	4707	25	2·07	·52	17·5	1·9	3·32	1·08
24	4630	34	1·55	·53	22	1·5	3·3	1·02
22	4578	45	1·24	·56	30	1·12	3·36	1·12
20	4517	75	1·03	·77	42	·87	3·65	1·16
18	4459	125	·72	·9	60	·61	3·66	1·2
16	4404	205	·62	1·27	87	·44	3·82	1·26
14	4349	225	·52	1·17	115	·33	3·79	1·24
12	4296	270	·43	1·16	130	·28	3·64	1·2
10	4245	320	·34	1·09	160	·23	3·68	1·14

Columns V. and VIII. are the most important. They are obtained by multiplying the luminosity by

the extinction and dividing by 100, which gives the extinction value when every ray is made of the luminosity of 1 candle at 1 foot. The figure gives this value for the red and green blind and for normal vision. It shows the difference in the extinction values.

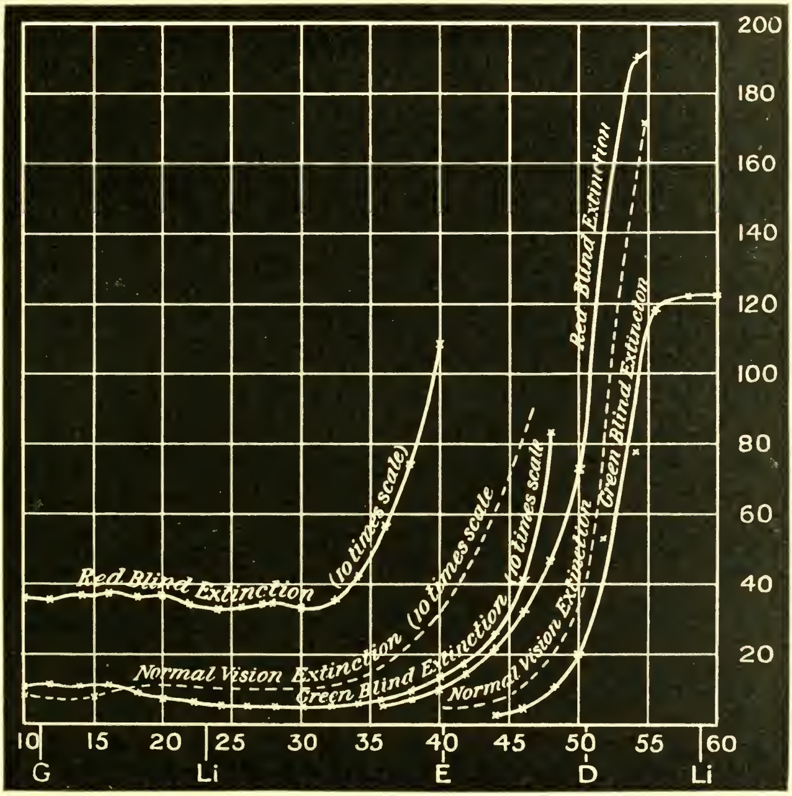


FIG. 89.—Red and Green Blind Extinction Curves, each ray having originally to them the luminosity of one candle. Normal vision extinction is shown as a dotted line.

The extinctions for the "one-candle luminosity" of each ray is practically the same *in the violet* for the normal colour vision as for the green blind. There is no reason why it should be different, since there is the

same proportion of red to blue sensation in both of them. This is only arrived at by making the normal colour vision and the green blind maxima of luminosity 100 and 80·6, which is that adopted from the sensation curves. The red blind shows an extinction more than three and a half times that of the green blind. In this case it has to be remembered that in this part of the spectrum the value of the red sensation is to that of the blue as 100 to 28. As the red blind have no red sensation, the extinction value should be $\frac{100}{28}$ or 3·57 greater. The agreement is fairly complete, but this again requires that the maximum luminosity of the red blind should be 32·8 when that of normal colour vision is 100, the same as that derived from the colour sensation curves. We are thus led to the conclusion that when the same white light falls on the retinæ of the colour blind, they suffer in the luminosity stimulated compared with normal vision. The relative areas of the luminosity curves are nearly—

830 for normal vision;
580 for green blind; and
250 for red blind.

If the normal vision has an impression of . .	100
the green blind has but	70
and the red blind only close upon . . .	30

This looks as if the colour blind were at a disadvantage in regard to the appreciation of light as a whole.

CHAPTER XX

INCOMPLETE RED AND GREEN COLOUR BLINDNESS

Besides the cases of complete colour blindness which we considered in the last chapter, there are still more numerous cases of what are called by some abnormal trichromatic vision,[1] but which it is preferable to call incomplete colour blindness, in which one of the pieces of apparatus in the eye is only partially sensitive.

Similarity of Sensation Curves in the Red and Green Blind compared with the Normal.

As far as incomplete blindness has come under the writer's observation, the luminosity curves of the red and green sensations are similar (in a mathematical sense) to those existing in normal vision—that is to say, if in the normal (say) red curve an ordinate of one colour indicates a perception of "a" red, and for the incomplete red blind a perception of "b" red, then in any other position in the spectrum that is not affected by yellow spot differences in absorption (so long as the luminosity does not come under the category of that of a feeble spectrum), the proportion of normal red perception to those of incomplete red blindness is as $a : b$. A reference to Table XXXVIII. will show why the place of maximum luminosity travels from SSN. 50 and SSN. 46 as blindness becomes more and more pronounced. The following table (Table LIII.) and

[1] See Paper No. 22.

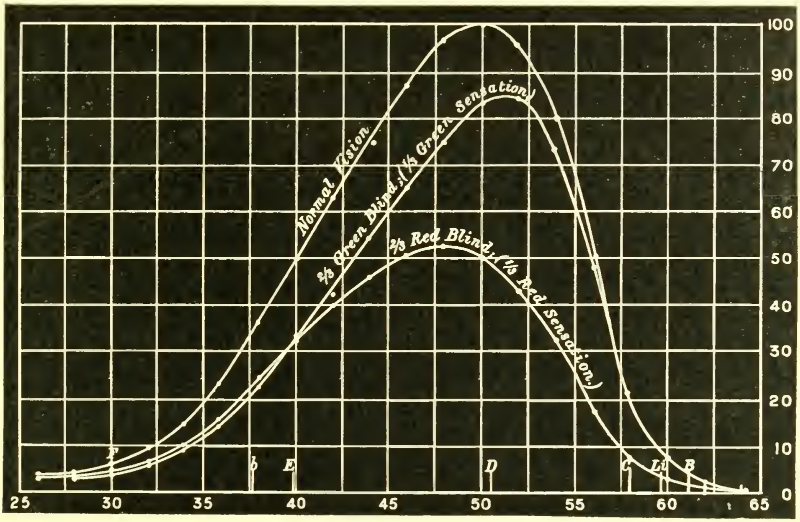
diagram give the luminosity curves for eyes which only perceive one-third of the red sensation and one-third of the green sensation. In the first the maximum is closely at SSN. 48 (λ 5720), and in the second at SSN. 51

TABLE LIII.—*Showing the Calculated Luminosities of Incomplete Red and Green Blindness.*

SSN.	λ.	Normal luminosity.	Red blind.				Green blind.			
			Luminosity of red blind.	⅓ RS.	GS.	BS.	Luminosity of green blind.	RS.	⅓ GS.	BS.
64	7217	·5	·2	·2	...	...	·5	·5	...	...
62	6957	2	·66	·66	...	...	2	2	...	...
60	6728	7	2·33	2·33	...	...	7	7	...	...
58	6521	21	7·14	6·93	·21	...	20·9	20·8	·7	...
56	6330	50	18·1	15·9	2·25	...	48·6	47·8	·75	...
54	6152	80	31·7	24·1	7·6	...	74·9	72·4	2·5	...
52	5996	96	42·3	26·9	15·4	...	85·8	80·6	5·2	...
50	5850	100	50	25	25	...	83·3	75	8·3	...
48	5720	97	53·5	21·7	31·8	·03	75·9	65·2	10·6	·03
46	5596	87	50·9	18·1	32·7	·1	65	54·2	10·7	·1
44	5481	75	45·9	14·5	31·3	·12	54·1	43·6	10·4	·12
42	5373	62·5	39·3	11·5	27·7	·12	40·9	31·6	9·2	·12
40	5270	50	32·8	8·6	24·1	·11	33·9	25·8	8	·11
38	5172	36	24·3	5·8	16·4	·09	23·7	17·5	6·1	·09
36	5085	24	16·6	3·7	12·8	·1	15·5	11·1	4·3	·1
34	5002	14·2	10	2·1	7·8	·12	8·9	6·2	2·6	·12
32	4924	8·5	6·1	1·2	4·8	·14	5·3	3·6	1·6	·14
30	4848	5·7	4·07	·82	3·08	·17	3·65	2·45	1·03	·17
28	4776	4	2·72	·59	2·03	·2	2·63	1·76	·67	·2
26	4707	2·8	1·86	·47	1·15	·24	2·03	1·41	·38	·24
24	4639	2	1·17	·38	·53	·26	1·59	1·15	·18	·26
22	4578	1·4	·82	·3	·27	·25	1·25	·81	·09	·25
20	4517	1·1	·59	·26	·1	·23	1·08	·77	·03	·23
18	4459	·86	·45	·21	·04	·2	·83	·62	·01	·2
16	4404	·7	·36	·17	·01	·18	·69	·51	...	·18
14	4349	·56	·284	·131	...	·154	·546	·392	...	·154
12	4296	·45	·237	·111	...	·126	·46	·334	...	·126
10	4245	·35	·182	·084	...	·098	·351	·253	...	·098

(λ 5922). The maximum at SSN. 49 (λ 5873) is reached when the red sensation is about two-thirds of the normal, at SSN. (47) (λ 5658) when it is about one-tenth of the normal, and at SSN. 46 (λ 5600) when there is no red

sensation. In the green blind, when there is no green sensation, the maximum is closely at SSN. 52 (λ 6000).



A is 67·2; B, 61·3; Red lithium, 59·8; C, 58·1; D, 50·6; E, 39·8; *b*, 37·7; F, 30·0; Blue lithium, 22·8; G, 11·2; H, −7·1.

FIG. 90.

Thus by observing the position of maximum luminosity we can form an approximate diagnosis of the amount of the defect and as to the sensation in which the defect exists.

First Method of Ascertaining the Amount of Colour Blindness.

Suppose that we have a luminosity curve taken by (say) an incompletely red blind eye, the question comes whether we can find still more exactly than by the position of the maximum ordinate the amount of deficiency that exists.

If by any means we can make the ordinates of the luminosity of any ray obtained by the colour blind of

proper height when such ordinate is compared with that obtained by normal vision, we can then compare all the ordinates of the curve given by the former with those given by the latter, for both curves will be on the same scale. If the trichromatic theory holds good, then the *difference* between the ordinates of the normal and the colour blind curves (say of an incompletely red blind) should, at every place in the spectrum (except may be in the blue), give a curve which is mathematically similar to the normal red sensation curve. The ratio of the ordinates of this curve to the ordinates of the normal red sensation curve will give the amount of red sensation *deficient* in the incompletely red blind eye.

When the incomplete blindness is to the green sensation, the same line of argument applies.

For convenience of reference, the table on p. 297 has been extracted from Table XXXVIII.

Two cases, one of incomplete red and the other of incomplete green blindness, will now be given. The luminosity measures were taken several years ago, and before the three sensation curves of the writer's (normal) eye had been found. (Without knowing whether a comparison of the luminosities to the colour blind eye of the spectral colours with those of a normal eye when using the same white would be of any value, in some cases measures by both were made and recorded. To these we shall refer later.)

It must be again pointed out that, owing to differences in the absorption by the macula lutea in different eyes, the blue sensation curve may not always be capable of the same treatment as the green or red sensation curves. But from the red end of the spectrum to about SSN. 40 (λ 5270)[1] this variation will not appreciably affect the results.

[1] See Paper No. 4.

TABLE LIV.—*Showing the Composition of the different Rays of the Spectrum, the Spectrum being formed of the light from the Arc with Sloping Carbons.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.
Standard Scale No. (SSN.).	λ.	Luminosity of spectrum.	Percentage composition of colours in terms of sensation.			Luminosity of sensation.		
			RS.	GS.	BS.	RS.	GS.	BS.
64	7217	·5	100	...	...	·5	...	...
62	6957	2	100	...	...	2	...	...
60	6728	7	100	...	...	7	...	...
58	6521	21	99	1	...	20·79	·21	...
56	6330	50	95·5	4·5	...	47·75	2·25	...
54	6152	80	90·5	9·5	...	72·4	7·6	...
52	5996	96	84·2	15·8	...	80·64	15·36	...
50	5850	100	75	25	...	75	25	...
48	5720	97	67·1	33	·02	65·16	32·01	·019
46	5596	87	62	37·9	·031	54·06	32·97	·027
44	5481	75	57·2	41·9	·042	43·3	31·5	·032
42	5373	62·5	55	44·9	·167	34·4	28·06	·042
40	5270	50	51·3	48·6	·117	25·61	24·3	·058
38	5172	36	48·5	51·3	·23	16·51	18·4	·083
36	5085	24	46·08	53·5	·42	11·09	12·83	·101
34	5002	14·2	43·79	55·34	·87	6·22	7·86	·124
32	4924	8·5	42·17	56·13	1·7	3·58	4·77	·145
30	4848	5·7	42·24	54·6	3·16	2·45	3·08	·174
28	4776	4	44·36	50·54	5·2	1·76	2·03	·202
26	4707	2·8	50·02	41·3	8·68	1·41	1·15	·243
24	4639	1·95	58·56	28	13·44	1·15	·53	·262
22	4578	1·4	65·56	16·3	17·64	·91	·27	·247
20	4517	1·1	70·72	8	21·28	·77	·1	·234
18	4459	·86	71·88	4·6	23·52	·62	·04	·202
16	4404	·7	72	2	25·76	·51	·01	·18
14	4349	·56	72	·5	27·44	·392	...	·154
12	4296	·45	72	...	28	·334	...	·126
10	4245	·35	72	...	28	·253	...	·098
8	4198	·26	72	...	28	·187	...	·073
6	4151	·18	72	...	28	·13	...	·051
4	4106	·14	72	...	28	·101	...	·039
2	4062	·1	72	...	28	·076	...	·028
0	4010	·06	72	...	28	·057	...	·022

In Table LV. we have the case of an incompletely red blind eye, W. The ordinates of luminosity as measured are given in column III. We have to obtain

a factor by which to multiply the numbers in this column to make it compare with the luminosity of normal vision given in Table LIV.

TABLE LV.—*Showing W.'s Curves.*

I.	II.	III.	IV.	V.	VI.	VII.
Standard Scale No. (SSN.).	λ.	Luminosity.	Luminosity × 0·455.	GS. + BS. from Table LIV.	Col. IV. – V.	$\frac{\text{RS.}}{6}$
60	6728	2·5	1·14	...	1·14	1·2
58	6521	7·9	3·59	·21	3·38	3·5
56	6330	20	9·1	2·25	7·85	7·8
54	6152	42·5	19·32	7·6	11·72	12
52	5996	63	28·66	15·36	13·3	13·8
50	5850	82·5	37·5	25	12·5	12·5
48	5720	92·5	42·08	31·8	10·3	10·8
46	5596	92·5	42·08	32·8	9·3	9·1
44	5481	85	38·7	31·4	7·3	7·2
42	5373	73	33·2	27·8	5·4	5·8
40	5270	62	28·2	24·2	4	4·3
38	5172	47	21·4	18·5	2·9	2·9
36	5085	32	14·6	12·7	1·9	1·8
34	5002	20	9·1	7·97	1·1	1
32	4924	12	5·46	4·9	·6	·6
30	4848	8	3·64	3·3	·34	·41

Let us take SSN.'s 58 and 46 in the first instance. The normal luminosities of these SSN.'s are 21 and 87 (see Table LIV.), and for W. 7·9 and 92·5.

From these we can form two equations. Putting z for the reduction of W.'s total luminosity ordinates and y for the reduction of those of his red sensation, the right-hand members of the equations will be formed from the red sensation luminosities of these two scale numbers (also given in Table LIV.). The left-hand member of the equations is the *difference* between the ordinates of

the normal and red blind curves at these scale numbers, which should be equal to the right-hand member—

$$21 - 7{\cdot}9z = 20{\cdot}8y$$
$$87 - 92{\cdot}5z = 54{\cdot}1y$$

From these we find $y = 0{\cdot}829$ and $z = 0{\cdot}455$. Making x the factor by which the normal red sensation has to be multiplied in order to give the amount of this sensation that is *present* in W.'s colour sense, $x = 1 - y$, and from these equations $x = 0{\cdot}171$. That is, when his curve is multiplied by 0·455, the difference between the ordinates of his curve and those of the normal give a curve which is five-sixths of the normal RS. curve.

Taking two other positions, viz. SSN.'s 50 and 44, we obtain the following equations:—

SSN. 50 . . $100 - 82{\cdot}5z = 75y$
SSN. 44 . . $75 - 85z = 43{\cdot}3y$

From this we obtain $y = 0{\cdot}85$, $z = 0{\cdot}45$, $x = 0{\cdot}15$. Taking the mean of y, we get—

$$y = 0{\cdot}835 \text{ and } x = 0{\cdot}165$$

—that is, W. has only 0·165 (or closely $\frac{1}{6}$) RS.

This number has been used in Table LV. to compare the red sensation curve of the normal with that of the incompletely blind.

Column I. is the SSN., II. the wave-length (λ), III. the luminosity of the colour blind, IV. the column III. $\times 0{\cdot}455$, V. (GS. + BS.) from the Table LIV.; VI. is (column IV. – column V.), and column VII. $\frac{1}{6}$ RS. reduced from Table LIV. It will be seen that after the (GS. + BS.) have been deducted from the reduced luminosity, we have a residue which gives (within limits of error of observation) the same numbers as those given by $\frac{1}{6}$ RS.

In this case, then, the incomplete red blind luminosity curve indicates the truth of the trichromatic theory, and also of the sensation curves of Table XXXVIII. The nearer colour blindness is complete, the greater the necessity for accuracy in the determination of the luminosity curves.

In the next table is given a determination of a case of incomplete green blindness, N.

Table LVI.—*N.'s Curves.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Standard Scale No. (SSN.).	λ.	Original Luminosity Readings by N.	Luminosity Readings from Diagram.	Luminosity ×0·82.	Luminosity of RS. + BS. from Table LIV.	Column V.–VI. showing N.'s GS.	GS. (from table) ×0·086
60	6728	8·7	8·7	7·13	7	·13	...
58	6521	25·5	25·5	20·9	20·79	·11	·18
56	6330	58·5	58·5	47·97	47·75	·22	·19
54	6152	87·5	89	72·98	72·4	·58	·51
52	5996	100	100	82	80·64	1·36	1·32
50	5850	93·5	94	77·08	75	2·08	2·15
48	5720	82·8	82·5	67·65	65·23	2·42	2·73
46	5596	69·6	69·6	57·07	54·29	2·78	2·81
44	5481	57	56·5	46·33	43·69	2·64	2·69
42	5373	46	45	36·9	34·73	2·17	2·38
40	5270	32·2	34	27·88	25·91	1·97	2·07
38	5172	23·7	23·7	19·43	17·59	1·84	1·6
36	5085	15	15	12·3	11·19	1·11	1·1
34	5002	8·8	8·5	6·77	6·34	·43	·68
32	4924	4·8	4·7	3·94	3·72	·22	·41
30	4848	3·2	3·5	2·87	2·62	·25	·26
28	4776	2·6	2·6	2·13	1·96	·17	·17
26	4707	2·2	2·1	1·72	1·65	·07	·09
24	4639	1·8	1·8	1·43	1·41	·02	·04
22	4578	1·5	1·5	1·23	1·1	·13	·02
20	4517	1·3	1·3	1·06	1	·06	·08

Taking SSN.'s 52 and 46, we form the following

equations as before; but from Table LIV. we use the *green sensation* luminosity :—

$$\text{SSN. } 52 \quad . \quad . \quad 96 - 100z = 15{\cdot}36y$$
$$\text{SSN. } 46 \quad . \quad . \quad 87 - 69{\cdot}6z = 32{\cdot}97\text{ [1]}$$

From these we find—

$$z = 81, \; y = 0{\cdot}906, \text{ and } x = 0{\cdot}094$$

Other pairs of equations can be formed by, say, SSN.'s 52 and 38 :—

$$\text{SSN. } 52 \quad . \quad . \quad 96 - 100z = 15{\cdot}36y$$
$$\text{SSN. } 38 \quad . \quad . \quad 35{\cdot}9 - 23{\cdot}7z = 18{\cdot}43y$$

From which we get—

$$z = 0{\cdot}81, \; y = 0{\cdot}90, \text{ and } x = 0{\cdot}10$$

We may take y as 0·90 approximately, which tells us the green sensation felt is only about one-tenth of the normal. The green sensation is shown in the table as 0·086 of the normal.

It was not possible to employ this method before the sensation curves of normal vision had been worked out, as, unless the composition of the colours in terms of sensation luminosity is known, y must also remain unknown.

One more example of the application of the formula to complete red blindness may be given. In the last chapter we have the luminosity curve of X. taken direct in column IX. of the Table L. We can apply the formula as in the other cases. Taking SSN.'s 50 and 40—

$$50 \text{ gives } 100 - 25z = 75y$$
$$40 \quad ,, \quad 50 - 24z = 25{\cdot}8y$$

[1] BS. is so small in this, as in the previous cases, that it may be neglected.

Here $y=1$ and $z=1$. That is, as $x=0$, the colour blindness to red is complete.

Taking SSN.'s 52 and 38, we get—

$$52 \quad . \quad . \quad 96-15 \cdot 1z=80 \cdot 6y$$

and
$$38 \quad . \quad . \quad 36-18 \cdot 5z=17 \cdot 5y$$

Here again $y=1$ and $z=1$, and from this pair the same deduction is made.

Direct Method of Determining the Colour Sensation Factor.

We will now give the method of calculating *directly* the amount of colour sensation which exists in an incompletely colour blind eye.[1] Suppose a person with normal vision and the person whose colour vision is defective each make luminosity measures of the same spectrum colours, the comparison white light in each case being the same. (The luminosity, it must be remembered, is measured by alteration in the intensity of the white beam.) Now the luminosity of the white light to the colour blind is less than to the normal eyed by exactly the amount due to the defect in the red or green sensation.[2] Hence, when the colour blind makes an observation, he is making the comparison with a lower luminosity of white than does the observer with normal vision. If the white light to each were *equally* luminous, their readings would give two curves of such a character that the difference in ordinates would be a direct measure of the defect, as in the previous method. As the white light is less luminous to the colour blind, we have to find to what extent the ordinates of his curve have to be altered.

[1] The method is adapted also for the completely colour blind.

[2] The case of blue blindness being exceedingly rare, and the luminosity of the blue sensation being so small, we need not consider here this form of defect.

Let x be the factor giving the amount of his deficiency in one sensation, and let m, n, and r be the luminosities of the red, green, and blue sensations of the ray which is to be measured.

Reverting to Table LIV., the total luminosities of these three sensations in the whole spectrum of white light are to normal vision closely as 580, 250, and 3. It will be seen that the blue luminosity has but small effect, and the red and the green are nearly as 7 to 3. The total luminosity for the normal eye is therefore 10. The luminosity of the defective sensation of the colour blind must be multiplied by a factor x. Supposing the reading for the normal to be a, and for the colour blind b, then we can make an equation which will contain x. To the red blind n remains unaltered, and r is negligible, so that we get the equation in the form—

$$\frac{a(mx+n)}{m+n} = \frac{b(7x+3)}{10} \quad \text{(i.)}$$ [1]

from which x can be determined. When there is no green sensation in the colour, as when the slit is at any scale number below SSN. 58, the equation becomes—

$$ax = \frac{b(7x+3)}{10} \quad \text{(ii.)}$$

For a green blind m remains unaffected, and the equation (i.) becomes—

$$\frac{a(m+nx)}{m+n} = \frac{b(7+3x)}{10} \quad \text{(iii.)}$$

and as there is no green sensation equation, (ii.) becomes—

$$a = \frac{b(7+3x)}{10} \quad \text{(iv.)}$$

[1] $(m+n)$ is, of course, the luminosity from Table XX.

Supposing $x=0$, which is the case when the colour blindness to red or green is complete, (i.) becomes—

$$\frac{an}{m+n}=\frac{3b}{10} \text{ or } b=\frac{10an}{3(m+n)}$$

and (iii.) becomes—

$$\frac{am}{m+n}=\frac{7b}{10} \text{ or } b=\frac{10am}{7(m+n)}$$

(iv.) becomes—

$$a=\frac{7b}{10} \text{ or } b=\frac{10a}{7}$$

which shows that the readings in the red are larger for the green blind than for normal vision.

The following observations made by a well-known man of science, whom we call Z., are given in Table LVII., and show the application of both methods of procedure :—

TABLE LVII.—*Showing Z.'s Curves.*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Standard Scale No. (SSN.).	λ.	Luminosity of Z. from Diagram.	Luminosity of Z. ×0·7.	Luminosity calculated from Table LIV., RS. being 0·35.	Standard Scale No. (SSN.).	Original observation.	A.'s observation.
60	6728	3·5	2·45	2·45	59·6	5	8
58	6521	12	8·4	8·38	57·6	16	25
56	6330	27	18·9	19	55·6	34	50
54	6152	47	32·9	32·9	53·6	53	68
52	5996	62	43·4	43·6	51·6	65	79
50	5850	73	51·1	51·2	...	...	...
48	5720	77	53·9	53·9	49·6	74	...
46	5596	74	50·8	51·7	47·6	76	...
44	5481	67	46·9	46·8	45·6	71	...
42	5373	57	39·9	39·8	43·6	64	...
40	5270	47	32·9	33·2	41·6	54	...
38	5172	35	24·5	24·55	39·6	44	...
36	5085	24	16·8	16·72	37·6	30	...
34	5002	15	10·5	10·16	35·6	19	...
32	4924	8	5·6	6·17	33·6	11	...
30	4848	4·5	3·15	4·06	31·6	7	...
					29·6	4	...

We will ascertain the *defect* of red sensation by the first method, and then confirm it by the second method. From the following table we take the scale numbers 52 and 46—

$$96-62z=80{\cdot}6y \qquad 87-74z=54{\cdot}2y$$

From this—

$$y=0{\cdot}67 \qquad z=0{\cdot}68 \qquad x=0{\cdot}33$$

SSN.'s 50 and 66 give—

$$100-73z=75y \qquad 50-27z=47{\cdot}7y$$

This makes—

$$y=0{\cdot}65 \qquad z=0{\cdot}7 \qquad x=0{\cdot}3$$

From SSN.'s 54 and 40—

$$80-47z=72{\cdot}4y \qquad 50-47z=25{\cdot}8y$$

From this—

$$y=0{\cdot}64 \qquad z=0{\cdot}72 \qquad x=0{\cdot}28$$

Taking the mean of these factors, we get—

$$y=0{\cdot}65 \qquad z=0{\cdot}7 \qquad x=0{\cdot}3$$

Here we have the *defect* in the red sensation is 0·7; therefore he must have only 0·3 RS. of normal vision.

Using formula (i.), at SSN. 59·6, the luminosity of the normal vision is 8, and of the colour defective 5—

$$8x=\frac{5(7x+3)}{10} \qquad x=0{\cdot}33$$

At another place in the red the readings were 25 and 16—

$$25x=\frac{16(7x+3)}{10} \qquad x=0{\cdot}35$$

At SSN. 55·6 the normal and colour blind readings

were 50 and 34. In this case $m=52{\cdot}7$ and $n=3{\cdot}3$. The equation then becomes—

$$\frac{50(52{\cdot}7x+3{\cdot}3)}{56}=\frac{34(7x+3)}{10}$$

This makes—

$$x=0{\cdot}31$$

Again, at 53·6 the two readings were 68 and 34. The equation is then—

$$\frac{68(74x+9{\cdot}2)}{83{\cdot}2}=\frac{53(7x+3)}{10}$$

This gives—

$$x=0{\cdot}376$$

Finally, at 51·6 the readings are 79 and 65. The equation is—

$$\frac{79(79{\cdot}5x+17{\cdot}4)}{96{\cdot}9}=\frac{65(7x+3)}{10}$$

This makes—

$$x=0{\cdot}33$$

The mean of the separate results gives 0·34 as the factor by which to reduce the normal sensation for this incompletely red blind. The factor derived from the first method was 0·3. This example shows that both methods give the same result within the limits of error of observation.

The sensation factors from numerous other luminosity curves, as made from the observations of incompletely colour blind persons, have been worked out, and so far no case has been met with to which these methods, founded on the normal colour sensations, as shown in Table XXXVIII., will not apply. Any small deviations are readily accounted for by errors in the

somewhat difficult measure of luminosity. Whatever may be the nature of the action on the visual receiving apparatus, whether it be mechanical or chemical, there seems to be no reason why similarity in the sensation curves of the colour blind, compared with those of the normal curves, should not always be maintained.

A determination of the amount of incomplete colour blindness, which existed in a recent case, is now given to show that complete luminosity curves are not required to ascertain the extent of colour sensation deficiency. The luminosities of only two points in the spectrum were determined by the colour blind (Jn.) and the writer. It was found by the examination that he was incompletely red blind, and the amount of red sensation deficiency was determined by the two sets of observations.

At SSN. 34, Jn.'s luminosity was 21, that of A. 45·5

,, 56·7, ,, ,, 28, ,, 43

At SSN. 34, the sensation luminosities from the table were—

$$\overset{\text{RS.}}{6{\cdot}22} + \overset{\text{GS.}}{7{\cdot}98}$$

and at SSN. 56·7—

$$\overset{\text{RS.}}{38{\cdot}45} + \overset{\text{GS.}}{1{\cdot}55}$$

The following equations were formed to determine the *defect* in red sensations:—

$$14{\cdot}2 - 21z = 6{\cdot}22y \qquad 40 - 28z = 38{\cdot}45y$$

from which y, the factor of defect, was 0·7, or 0·3 was the amount of his red sensation, and z, the factor by which to reduce the luminosity, was 0·47.

Next, using the determinations of the luminosity,

*

the following equations were obtained, where x is the factor for RS. existing in Jn.'s sensation :—

$$\frac{43(38{\cdot}45x+1{\cdot}55)}{40}=\frac{28(7x+3)}{10} \qquad x=0{\cdot}314$$

$$\frac{15{\cdot}5(6{\cdot}22x+7{\cdot}98)}{14{\cdot}2}=\frac{21(7x+3)}{10} \qquad x=0{\cdot}29$$

The mean of the two gives 0·3 as the factor, and agrees with the preceding determination. It is to be noticed that the blindness must be to the red, for if we form equations by the first method, supposing green blindness, with the same numbers we get—

$$14{\cdot}2-21z=7{\cdot}98y \qquad 40-28z=1{\cdot}55y$$

This makes y a minus quantity, which is impossible.

Again, with the second method, we should have, with SSN. 57·6—

$$\frac{43(38{\cdot}45+1{\cdot}55x)}{40}=\frac{28(7+3x)}{10}$$

where x is greater than unity.

Caution as to the luminosity method of getting the factor of deficiency where there is a suspicion that the macula lutea is very highly or very little pigmented is here interpolated, and should be read into the results given in the last chapter. It is safe in such cases to confine the luminosity measures to SSN.'s greater than 42 or 44. With lower SSN.'s the question of pigmentation may cause a difference in the factors obtained

CHAPTER XXI

COLOUR EQUATIONS FOR THE DETECTION OF COLOUR BLINDNESS

In this chapter the method of detecting colour blindness, complete or incomplete, by means of colour equations made from the spectrum colours will be considered.

Description of White by the Colour Blind.

When a patch of white light is shown to any of the complete or incomplete colour blind, they recognise it as their own white; though not infrequently when they observe it in contrast with another colour, the latter will miscall it. But, placed by itself, every person, colour blind or not, will name it as white. If we place three slits in the spectrum, one in the red, where it has been shown that only the red sensation is stimulated, and another in the green, where the sensation curves tell us that all three sensations are excited, but the green mostly, and in excess of the other two, and the third in the violet, where only the red and the blue sensations are stimulated, we shall be able, by collecting the rays on to a patch and altering the apertures of the slits, to make a mixture which will match a patch of the pure white when the two patches of light are placed side by side on a screen. The colour patch apparatus, which has been described in Chapter IV., p. 38, is perhaps the simplest apparatus with which to compare the mixed lights with the white. The normal eye will

make his match, which will be exact to him as his white. If a completely red blind (the eye which sees a shortened spectrum) is asked if the match is satisfactory to him, he will say that it is. The completely green blind will give the same answer. If the red slit[1] be completely closed, the red blind will see no difference in the match, for he has no red sensation which can be stimulated. If, however, a partially red blind person be asked if the normal eye's match is exact, he will say it is not, but that the composite white is too green. By opening the red slit, or closing the green slit gradually, a point will be reached in which he says the match is exact. To the normal eye the match will appear red. If the widths of the slits be measured, both for the normal and also for the colour blind, when the matches to the one and the other are correct, and if both measure the respective luminosities of their composite light patches (by opening or closing the rotating sectors placed in the path of the white beam which forms the white patch), we have, when the positions that the slits occupy in the spectrum are known, a means of calculating the sensation deficiency in the partially colour blind. If the deficiency in the colour blind be in the green sensation, the normal eye's composite white will appear to him as too red. By opening the green slit gradually, a width of slit will be found which makes the patch appear to the partially green blind a match to the white. To the normal eye it will appear green, more or less pronounced, according to the degree of lack of response to the stimulation of the green perceiving apparatus in the colour blind eye. The slit apertures, and luminosity, of the composite "white," are measured as before.

[1] In this chapter, as in others, the red, green, and violet slits are the slits through which tht red, green, and violet rays pass.

Formation of Colour Equations.

We will deal with the equations thus formed, which will be in the form of—

$$(a) \text{ red} + b \text{ (green)} + c \text{ (violet)} = m \text{ (white)}$$

first of all without reference to the numerical value of m, the sector or annulus reading.

The following are two cases which are dealt with by this method :—

The three slits were placed at SSN. 59·8 (the position of the red lithium line), at SSN. 38·3 (near the green Mg line), and at SSN. 8·5 (which is of less wave-length than G.). A normal eye formed an equation to match the hue of white—

$$100 \text{ (R.)} + 40 \text{ (G.)} + 55 \text{ (V.)} = \text{White}$$

For convenience in calculation, we can convert the equation into another, in which G. is 100—

$$250 \text{ (R.)} + 100 \text{ (G.)} + 137 \text{ (V.)} = \text{White}$$

The comparative luminosities of the rays passing through equal slits at the three points in the spectrum which they occupy were R. = 10, G. = 43, V. = 0·87. In the red there is only red sensation. In the green there are red, green, and blue sensations with luminosities of—

RS.	GS.	BS.
21·18,	21·65,	0·1056

respectively, which make up the luminosity 43. In the violet ray the luminosity is $0{\cdot}87 \times 135$, of which 28 per cent. is blue sensation and 72 per cent. red sensation.

We will next see how much white the green ray contains. This is best done by changing the ordinates

of the three sensations in the green into ordinates of the three sensation curves of equal stimulation—that is, when the areas of the three sensation curves are equal. In these experiments the source of light was the arc light with a horizontal carbon for the positive pole (see Table XL., p. 244). To make the green curve equal to the red curve, the former had to be multiplied by 2·21 and the blue curve by 117. The three sensation curves thus multiplied gave ordinates which when equal make white. Applying these factors to the components of the green ray, we get—

$$\text{G.} = \overset{\text{RS.}}{9{\cdot}46} + \overset{\text{GS.}}{16{\cdot}55} + \overset{\text{White.}}{26}$$

The 26 white evidently does not alter the hue of the mixture which forms white.

The equation, when converted into luminosities, neglecting the white, becomes—

$$\underbrace{\overset{\text{RS.}}{2500}}_{\text{R.}} + \underbrace{\overset{\text{RS.}}{946} + \overset{\text{GS.}}{1655}}_{\text{G.}} + \underbrace{\overset{\text{RS.}}{66} + \overset{\text{BS.}}{25}}_{\text{V.}} = \overset{\text{RS.}}{3512} + \overset{\text{GS.}}{1655} + \overset{\text{B.}}{25}$$

Let us consider the conditions under which a colour blind person makes a match with a white compared with one made by normal vision. Suppose we take as an example a partially green blind as making the equation.

Firstly, if we call A the luminosity of the white to the normal, and the luminosity of the white to the green blind as A′, and let x be the factor of the green sensation deficiency. If the normal equation in sensation luminosities is—

$$\overset{\text{RS.}}{a} + \overset{\text{GS.}}{b} + \overset{\text{BS.}}{c} = \text{White}$$

then the colour blind equation must be—

$$\overset{\text{RS.}}{(a} + \overset{\text{GS.}}{bx} + \overset{\text{BS.}}{c)}\,\frac{A}{A'} = \text{Colour blind white}$$

since the only effect of the alteration in the white to be matched is to diminish its intrinsic luminosity.

If we disregard the white luminosity, it is evident that the equation for the colour blind can be directly compared with the normal.

A Red Blind Equation examined by First Method.

In the case of a red blind, his mixture to match his white was—

$$100\ (\text{R.}) + 27\ (\text{G.}) + 45\ (\text{V.}) = \text{White}$$

If we make the green 100 as before, it will be seen that the RS. of the colour blind compared with that of normal vision will give us the value of x. In the above equation, doing this, we get—

$$\overset{\text{R.}}{370} + \overset{\text{G.}}{100} + \overset{\text{V.}}{167}$$

Working this out into the normal luminosity of the sensations, we get—

$$\underbrace{\overset{\text{RS.}}{3700}}_{\text{R.}} + \underbrace{(\overset{\text{RS.}}{946} + \overset{\text{GS.}}{1655})}_{\text{G.}} + \underbrace{(\overset{\text{RS.}}{104} + \overset{\text{BS.}}{41})}_{\text{V.}}$$

or

$$\overset{\text{RS.}}{4750} + \overset{\text{GS.}}{1655} + \overset{\text{BS.}}{41}$$

To the same amounts of green the amount of red in the normal is to the red of the colour blind as—

$$3512 \text{ to } 4750$$

that is, the colour blind has only 0·75 the normal R. sensation.

The figure obtained by the luminosity method described in the last chapter was the same, viz. 0·75 RS.

It is to be observed that the result is obtained by considering the mixture from a normal eye point of view.

In regard to the white in the green ray, it is present to the colour blind as it is to the normal vision, though it is different in hue, but like the white he matches, and consequently differs in luminosity, but as it has, as in the case of the normal eye, no effect on the resulting hue, it is not taken into account. It has to be remembered that to get sensation curves of equal areas for the colour blind, the factors have to be increased for the green curve in the case of partial green blindness, and a factor has also to be introduced for the red curve in the case of partial red blindness.

Another case is one of green blindness, which will be the second example of this method of treating the equation. The observer Y. is a case of interest, as he has often been quoted as an example of abnormal trichromatic vision.

The measures were taken in the presence of Dr. W. Watson, F.R.S., with the colour patch apparatus. The equation of Y. for white was—

$$98\ (\text{R.}) + 100\ (\text{G.}) + 67\ (\text{V.}) = \text{White}$$

Treating this equation as before, we find that to a normal eye the equation in luminosities becomes—

$$\begin{array}{ccccc} \text{RS.} & & \text{GS.} & & \text{BS.} \\ 1926 & + & 1655 & + & 16 \end{array}$$

In this case, to get the green sensation present in the colour blind eye, we must *divide* Y.'s RS. (red sen-

sation) by the normal red sensation or $1926/3562 = 0{\cdot}54$ closely of normal GS. Y.'s luminosities at five different places in the spectrum (see previous chapter for method) gave a mean value of 0·58 GS. The pigmentation of Y.'s macula lutea was far *above* the ordinary pigmentation, and the caution given at the end of Chapter XX. was observed.

The "white" equations treated this way give trustworthy measures of deficiencies where the factors are not very small.

Second Method of solving a Colour Equation.

So long as the factor for the sensation is not below 0·5, it may be followed, but below that point there may be erroneous estimates derived from the calculation. The normal eye cannot detect within 2 per cent. of excess of a colour matched to a white, and guard had to be taken against this in forming colour equations, to ascertain the spectrum colour sensation curves for the normal eye. There is reason to believe that for small sensation factors a much larger quantity of colour may be added to white, and of white to the colour, than can be added by the normal eye without detection. It has already been pointed out that, to a completely red blind, the match to the normal eye is satisfactory, although it is just as satisfactory to him if the red slit be closed. Indeed, any amount of red may be added to his white without altering the match. We can understand that, with an eye which only has, say, 0·05 RS., an almost equal amount of red might be added to the white and not be perceived. As the factor increases, the amount of white that can be added to the red, or of red to the white, without altering the hue, will be less—and so also

with the green sensation. It seems that the ordinates of a curve that may represent the amounts that can be added may probably be the ordinates of an hyperbola.

Whatever may be the reason of the want of perception of the added colour, we know that the want exists, and the second method of treating the equation gets over any difficulty on this account. The method is a combination of the first method with that of the luminosity method. If when the white is matched in hue by the colour blind, he is also required to make a determination of the luminosity of his composite white, and if the normal eye also takes a measure of the luminosity of the colour blind composite white, or takes a measure of the luminosity of his own composite white, there are sufficient data with which to calculate the sensation deficiency. It should be noticed that the luminosity of a *composite white* against a pure white is very easily measured. There is no difficulty in the observation, though it may exist to some observers when the luminosity of a *colour* against white has to be determined.

We will suppose that the following equation has been made by a green blind:—

$$a\,(\text{R.}) + b\,(\text{G.}) + c\,(\text{V.}) = p \text{ of sector to the colour blind}$$

and that to the normal eye it has a luminosity of m. It is only necessary to take into account the luminosities of the red and green sensations, since those of the blue sensation are very small compared with them.

Let us turn the colours into sensation luminosities, this time not calculating out the white in the green ray, and the equation becomes to the normal eye—

$$\overset{\text{RS.}}{a} + \overset{\text{GS.}}{b} = hm$$

h being the factor which makes $m = (a + b)$. Using h for the green blind equation, we have hp, but to the colour blind p is dependent on the area of his total luminosity curve, which is smaller than the area of the normal luminosity curve of the spectrum.

Let A be the area of the normal luminosity curve (Table XL.), and A′ the area of the colour blind luminosity curve.

To make p balance the composite white to the normal eye, the left-hand members of the equation must, as on p. 313, be multiplied by A A′, and calling x the factor of the sensation deficiency for the colour blind, we get for green blindness—

$$a\frac{A}{A'} + bx\frac{A}{A'} = hp$$

or

$$a + bx = hp\frac{A'}{A}$$

If the value of A be 10, *i.e.* $(\overset{\text{RS.}}{6{\cdot}8} + \overset{\text{GS.}}{3{\cdot}2})$[1]—

$$A' \text{ is } \overset{\text{RS.}}{6{\cdot}8} + \overset{\text{GS.}}{3{\cdot}2x}$$

$$A' \ A = (0{\cdot}68 + 0{\cdot}32x)$$

$$x = \frac{0{\cdot}68hp - a}{b - 0{\cdot}32hp}$$

If the deficiency were in the red sensation—

$$x = \frac{0{\cdot}68hp - b}{a - 0{\cdot}32hp}$$

The value of h may be determined, we said before, by the normal eye measuring his composite white against the same white patch which the colour blind matched.

[1] These numbers are derived from the luminosity sensation (R. and G.) curves of the light used in these measures, Table XL., p. 244.

It will be noticed that x is determined regardless of the true amounts of RS. and GS. on the left-hand side of the equation.

The following is an example of what may be called a glaring case of an untrue equation being formed by a nearly completely red blind person (S.). The mean of two of his equations was—

$$30\ (\mathrm{R.}) + 16{\cdot}75\ (\mathrm{G.}) + 12{\cdot}75\ (\mathrm{V.}) = 27{\cdot}2° \text{ of sector in white}$$

We may neglect the luminosity of the blue sensation and use only the red and green.

Converting the above into luminosities of RS. and GS. (in this instance not taking away the white which is in the green ray, as all its components of red and green sensations are required), viz.—

$$\overset{\text{RS.}}{21{\cdot}18} \text{ and } \overset{\text{GS.}}{21{\cdot}65} \text{ (see \textit{ante})}$$

and having found from a normal vision equation that $h=41$, we get—

$$\overset{\text{RS.}}{300} + (\underbrace{\overset{\text{RS.}}{355} + \overset{\text{GS.}}{365}}_{\text{G.}}) = 27{\cdot}2 \times 41(0{\cdot}68x + 0{\cdot}32)$$

or $$\overset{\text{RS.}}{655x} + \overset{\text{GS.}}{365} = \overset{\text{RS.}}{758x} + \overset{\text{GS.}}{357}$$

From this we get—

$$x = 0{\cdot}08 \text{ nearly}$$

or S. possesses about 0·1 of the normal RS.

Using the first method of treating the equation, he would have been supposed to have 0·8 RS. His RS., calculated by the luminosity method given in Chapter XX., was 0·1 closely.

A case of green blindness (Wn.), which gave a fairly large deficiency by the luminosity method, is now given. His equation to white was—

$$30\,(R.) + 32\,(G.) + 39\,(V.) = 23 \text{ White}$$

At the same time, and using the same comparison white beam, a person having normal vision found an equation which gave a factor h for the white of 67.

Applying this factor to Wn.'s equation, we get as the luminosity equation—

$$\overset{\text{RS.}}{978} + \overset{\text{GS.}}{691x} = 1048 + 493x$$

$$x = 0{\cdot}35 \text{ of normal GS.}$$

His factor of GS., obtained by the luminosity method, was about 0·33.

If we treat Wn.'s equation by the first method, we get a factor of 0·54.

These two cases confirm what has been said as to non-recognition of white or colour when added above the 2 per cent. limit.

It must be remembered, in accounting for the lack of accuracy in mixing the colours to form white, that to the normal eye the white of the largely deficient green blind is a slightly pale purple, and that of the largely deficient red blind a slightly pale sea green.

[In the examples given, the position of the green slit may seem not to be the best one to use, as this ray, besides the white, contains both green and red sensations; but for general purposes it is a good one. The ideal position is that the ray which passes through the slit should only be composed of white and green sensations. This position on the standard scale with the arc light and horizontal carbon is close to SSN. 36, but it

must be remembered that this position is one in which the rays are largely absorbed in most instances by the yellow spot.

When the distance of the eye from the screen is kept absolutely constant, it is preferable that the ray should contain white, green, and a trace of blue sensations, rather than white, green, and red sensations, as the latter imposes a limit on the green sensation factor. In the position SSN. 38·3, which the slit has occupied in the above examples, the limit of the factor is about 0·26 GS. For the red deficiency there is no limit when using that position.]

Examples only of incomplete colour blindness have been given. When the colour blindness is complete, only two slits need be opened. The third (red or green) may be opened to any extent, but the last method will show the "completeness" of the sensation's deficiency.

CHAPTER XXII

MATCHING A PURE COLOUR BY A MIXTURE OF TWO COLOURS, AND A MIXED COLOUR MATCHED BY ONE PURE COLOUR.

A FAVOURITE plan in Germany for a semi-quantitative measure of colour sensation deficiency is that which originated with Lord Rayleigh. This method is one of mixing red and green to match the sodium D light of the spectrum. There are special instruments extant for this purpose, and note is directed to be made of the quantities and intensities of each colour which are required to give a match to this light. There are, however, no directions given by which the factor of deficiency is to be ascertained, though it would be easy to give them when the positions of the red and the green in the spectrum are known.

Matching of the "D" Light.

If we place two slits in the colour patch apparatus in the same positions that we have already used in the red and the green, we can make an approximation to the deficiency by the match made of the D light. The match made will be of the same *hue* as the D light when a little white is added, for there will be white in the mixed colours. In Chapter XVII. it is shown that from the scarlet to the greenish yellow in the spectrum the addition of white to a colour will make its hue yellower, and from the blue-green to the green the same "yellowing" of the hue would be apparent.

X

In matching the D light with a green (every green contains white) and a pure red, the true proportion of RS. and GS. in the match will not be quite identical with those in the D light itself. If the colour to be matched be at SSN. 48·7 of the standard scale, which is where the red and green sensation curves of the arc light spectrum (of equal areas) cut, this would not occur, since at that point no change in hue is found when white light is added to it.

If, however, a light such as the paraffin light is employed as the source for the spectrum, the red and green curves of equal areas will cut very close to D in the spectrum, and the white light existing in the green ray, when calculated out (as has been done for the arc light), will be very nearly the hue of the D light, so that there will be no shifting of hue. It is necessary to mention this, as, if the match is to be used for ascertaining colour sensation deficiency, the sensation curves for the light source used must be employed in the calculations.

A gauge of accuracy of measurement is the closeness with which the mixture of red and green made by a normal eye shall give the hue and the proportion of sensations existing in the D light.

The writer's mean equation for the D light, with the slits in the same position as before, is—

$$447\ (\text{R.}) + 100\ (\text{G.}) = \text{D light}$$

This, when worked out with luminosities, gives a percentage value of—

$$\overset{\text{RS.}}{77} + \overset{\text{GS.}}{23}$$

as contained in the mixture, neglecting the white. This is very slightly (0·3) less red than is contained in the

D light, and is probably to be accounted for by the white existing in the green ray.

There is in these D equations, as in the equations for white light, the same possibility of their failure when the sensation factor of deficiency is small owing to the non-perception of added colour, but if the luminosity of the D light (or other selected ray) be measured against the mixed colours, the difficulty, as before, vanishes.[1]

Matching the colour of Chromate Potassium with a Single Ray.[2]

In Chapters XVIII. and XIX. several methods have been described for ascertaining quantitatively the amount of green or red sensation which exists in the incomplete green or red blind eye as compared with the normal eye. In Table XXXVIII., at page 239, is to be found the percentage composition of the tabulated rays of the spectrum, and Table XXXIX., p. 242, gives the amount of white (where there is any) which exists in these several rays. For reasons given later, attention must again be called to the fact that if the colour at this point is mixed with blue at SSN. 23, by the proper adjustment of width of slits a match can be made of the white light which goes to form the spectrum. (Whatever the source of light, the curves of equal areas must be calculated for it, as the point of intersection varies according to the light employed.)

Looking at Table LIV., p. 297, it will be seen that from SSN. 50 to the extreme red no measurable quantity of blue is to be found. If the beam of (say) the arc light has to pass through a cell containing a saturated solution of potassium chromate of about $\frac{3}{4}$ inch in thickness, the light will become yellow with very little blue

[1] See Chapter XVII. [2] See Paper No. 26.

in its spectrum. If in the colour patch apparatus a slit be caused to traverse the spectrum, a position will be found where the ray passing through it exactly matches the hue of the white light after transmission through the chromate solution. This will be at SSN. 49·6 (λ 5830) to the normal eye. This, like other rays, contains a fixed ratio of green to red sensation, but no measurable blue, and therefore no white which could alter the hue. Making the red sensation unity, it will be found that the green sensation is ·385 at SSN. 49·6.

The following table gives the ratios of green to red for the standard spectrum scale, making red unity, as also the wave-length scale for the like ratios :—

Table LVIII.

SSN.	GS.	λ.	GS.	GS. corrected from Diagram.
56	·047	6300	·050	·050
54	·105	6200	·080	·080
52	·187	6100	·127	·127
50	·333	6000	·185	·185
48	·475	5900	·280	·280
46	·603	5800	·390	·385
44	·717	5700	·500	·490
42	·830	5600	·600	·595
40	·934	5500	·700	·700
38	1·05	5400	·805	·805
36	1·16	5300	·910	·910
34	1·26	5200	1·015	1·015
32	1·33	5100	1·135	1·120
30	1·29	5000	1·260	1·225
28	1·14	4900	1·340	1·330
26	·82			

From these tables diagrams on a large scale can be drawn from which the ratios of red to green can be read off for any scale number (or wave-length). Fig. 91 gives such a diagram on a small scale.

If an incompletely green blind makes a match, the

slit would have to be moved towards the red. When he considers the match correct, the scale number of the ray is read off and a reference is made to the diagram. Thus, suppose that the mean reading of the match were 52, the amount of GS. to RS. to the normal eye would be 0·187. By dividing this number by ·385 (the number

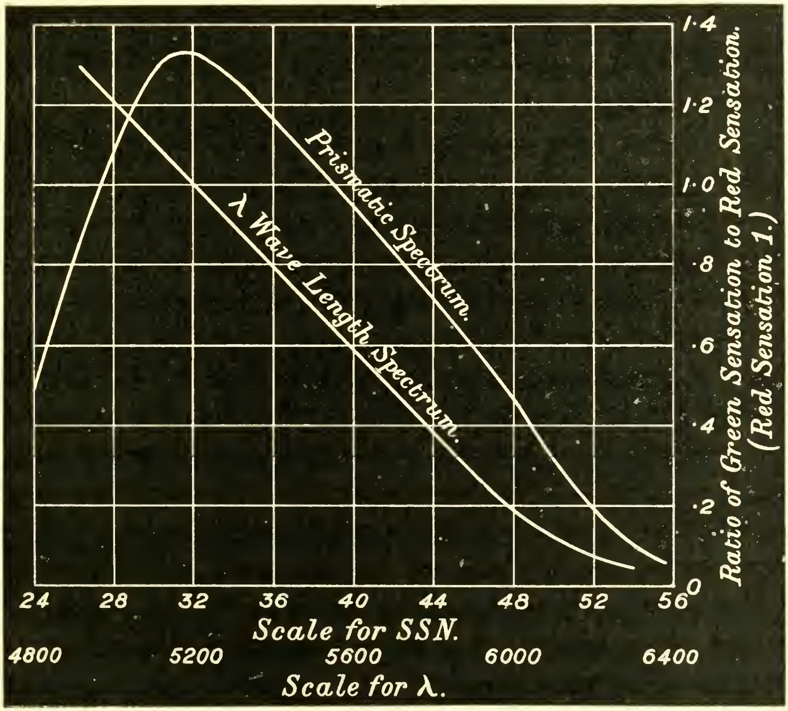


FIG. 91.—Figure showing ratio of green to red sensation.

corresponding to the match for the normal eye), we get very closely 0·5, and this would be the amount of green sensation (compared with 1 for the normal eye) that the green blind possesses. Again, if we have the match by an incompletely colour blind at SSN. 46, we know at once he is incompletely red blind, as that SSN. contains

·603 of GS. 1 of RS. Dividing ·385 by ·603, we make the amount of RS. which he possesses as ·638.

An inspection of Fig. 91 shows that the maximum ratio of green sensation is near SSN. 30 when it is about 1·32. As the normal match has ·385, and as this has to be divided by the incompletely red blind person's ratio, it shows that no smaller factor of red sensation can be found than $\frac{\cdot 385}{1 \cdot 32}$ or ·29 RS.[1] For the green blind the smaller factor can be found, but the test is especially useful for large factors.

One example of the accuracy and delicacy of the test is now given. The normal eye made a match at SSN. 49·6, and an incompletely colour blind at SSN. 41·5. The former, as before, has a ratio of ·385, and the latter of ·855 red to green sensation. This gave a factor of ·45 for the green blind's GS.

The same person was tested by the luminosity method described in Chapter XVIII., which also made him have ·45 GS. From his colour equations his factor was ·37. The mean of the three values derived for his factor is ·42 but ·45 is most likely to be right.

In making these tests, the luminosity of the white beam passing through the chromate is first made to be about the same as that of the light coming through the slit. Four matches of colour are sufficient, two by reaching the match from the red side, and another two from the blue side of a first approximate match. A mean of the four readings is taken as being the position of a correct match, though not unfrequently all four are the same.

It may be advisable to indicate how the amount

[1] When bichromate of potassium is substituted for the chromate, smaller factors can be measured.

of displacement, if any be possible, of one or other of the green and red sensation curves can be determined.

At p. 323 it was pointed out that when a slit was placed in the ray where the two green and red sensation curves of equal area cut, the addition of pure blue enabled a match to be made with the white of the light which formed the spectrum.

Let *aa*, *bb* be two portions of the green and red sensation curves respectively which cut at O and having

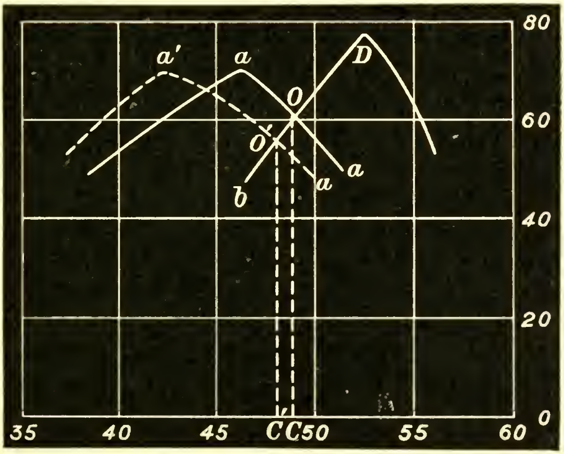


FIG. 92.

an ordinate OC, then a slit placed at C in the spectrum will allow a ray to pass, which with the blue of SSN. 23 will match white. This holds good also for the colour blind, since the curves under consideration are "equal area" curves. The white they would match would of course be the "colour blind white." If the green curve were shifted to the left, the curves would no longer cut at O but at O′, and the slit would have to be placed at C′ before white with the blue would be produced. The same occurs also should the red curve be shifted. By

making observations such as this entails, any shift can be noted. Should such an alteration in the position of the intersection of the two curves take place, the difference in position of the slit placed in the yellow must be added to, or subtracted from, the position of the normal match for the eye when the colour of the chromate is used for matching. If there be colour blindness, this corrected position, if ever found, might have to be used for comparison.

It may be remarked that by the luminosity method of ascertaining the factor, a non-normal sensation would be closely the mean between the factors shown on the red side of the maximum luminosity, which might differ slightly from those obtained on the blue side.

CHAPTER XXIII

MEASUREMENT OF GREEN OR RED SENSATION DEFICIENCY BY MEANS OF COLOUR DISCS

THE methods of ascertaining the amount of colour sensation deficiency in the colour blind have so far depended on measurements made in the spectrum itself, but attention must be called to a method which is independent of a spectrum apparatus. It is true that its accuracy in the first instance depends upon measurements made in the spectrum; but when once made, a colour sensation deficiency (within limits) can be determined without further reference to it. We mean by colour disc equations. Given three discs of equal diameter (say 4 in.), capable of interlacing and of being rotated, one of which is painted with a red pigment, another with a green pigment, and the third with a blue pigment: by altering the angles of the interlacing discs, a grey can be formed on their rotation,[1] and this can be matched by a white and a black disc of, say, 6 in. diameter, also rotating on the same spindle. Of course there is nothing new in this method, but the method of treating the equations given by the colour discs will be found new in some details. Colour discs can be used *in any light*, but to be really useful for calculation the kind of light should be known. The colours of the discs themselves are the only part of the apparatus which requires careful measurement, and this must be done in the spectrum. The composition of the colours must be ascertained in terms

[1] See Chapters XI. and XVI.

of the three colour sensations, and the luminosity of the colours must also be known. The former and the latter will both vary according to the nature of the light in which they are viewed.

Spectrum Composition of the Pigments.

We may proceed in ascertaining the composition of the pigment colours by the method given in Chapter XVI.

The compositions of the pigments are there given for the light of the electric arc; but when the luminosity curve of the spectrum of any other light is known, the sensation luminosities in the pigment colours can be at once calculated from the table at p. 239.

Let the amount of each ray which is reflected from the pigmented surface be measured. Such a method also gives the luminosities in terms of the total white light used to form the spectrum. This is an exact method, but a somewhat long one, and perhaps it tells more about the pigment than is necessary to know for the purpose that is in view. All we require to know, as said before, is the composition (in sensation luminosity) and the total luminosity. The former we can arrive at in a very simple manner. Let us place a square piece of the pigmented paper in the colour patch apparatus, and side by side with it an equal square of a white surface. Let the pigment patch be illuminated by the light in which the discs are to be used, say, gaslight, incandescent light, &c. (daylight is out of the question, as it is so variable in quality), whilst the other is illuminated by the arc light coming through the three slits in the spectrum, as has already been described. By placing a rod in the path of the beams, the two illuminations may be separated,

but can be caused to touch one another. All we have to do is to match the *colour* of the pigment, as seen in the light by which it is illuminated, with the mixture of the rays coming through two or three of the slits. The light itself is also evaluated by making both patches of zinc white, one being illuminated by the light to be employed. Having done this, the width of slits must be measured as before described. When converted into luminosities, and the luminosities into the respective sensations existing in the rays, the relative amounts of the sensations stimulated by the pigments and by naked light can be calculated. By making the patches equally bright, the relative *luminosities* of the pigments compared with that of the light illuminating the white can also be ascertained with great exactitude if the pigmented paper is removed and a second square of white paper is substituted for it. The sensation values of the three coloured discs for the light in which they are to be viewed will now be known, as also the luminosity.

An example will show that both methods of ascertaining the sensation luminosity values of the light and pigments give within small limits the same values.

The comparison light was the reflected arc light as used in the colour patch apparatus, see p. 39, with a cell of potassium chromate placed in the beam. The absorption of the chromate solution was measured and converted into luminosities by the method given on p. 76. The red and green sensations were calculated. The intensity of the reflected light from the pigments was measured, as given on p. 78, and from their luminosity curves and percentage sensation curves (Table XXXVIII.) the luminosities in red and green sensations were calculated.

The colour of the light passing through the chromate

solution on to the white and on to the pigment patches was matched by a mixture of the rays passing through the red and green slits in the spectrum, and the sensations were calculated as before, with the following results :—

Light.	First Method.		Second Method.	
	RS.	GS.	RS.	GS.
Chromate on white .	70·8 +	29·2	71·1 +	28·4
Chromate on green pigment . . .	62·7 +	37·3	62·6 +	37·4
Chromate on red pigment . . .	85·3 +	14·7	84·7 +	15·3

Using the Colour Discs.

To use the discs to give true equations, the illumination must be that of the same kind of light as that in which their sensation values have been determined. It will not do, for instance, to use the values obtained for the arc light in daylight or in gaslight. If an incandescent light (say) is used for the illumination of the pigment during measurement, the discs must be rotated in the same light. Stress is laid on this, as it is not uncommon for those using colour discs to be lax as to the light they use.

The three discs are placed on the spindle of the whirling apparatus (a small motor is handy for the purpose) with the interlaced black and white discs behind them. The coloured discs are altered till a grey is obtained which matches the grey of the rotating black and white discs.[1] The angular apertures of the exposed

[1] It is well that the matches should be made with the light falling perpendicularly on the discs and the observer being as nearly as possible facing them.

parts of the several discs are all measured and the values recorded as—

$$a \text{ red} + b \text{ green} + c \text{ blue} = m \text{ white} + (360 - m) \text{ black}$$

The amount of white reflected from the black is measured, and if n be the factor the white becomes $m + (360 - m)\, n$.

It is essential in some cases that both the greys should be of exactly the same brightness. (It need scarcely be said they should be identical in hue.) Everything depends, for a true determination of the amount of colour blindness, on the true matches being made.

It may here be emphasized that both luminosity and sensation composition will vary in every light, so that exactitude of match in any light but that in which the measurements have been made is labour thrown away.

Examples of Colour Disc Equations.

We will now give examples of the mode in which the equations should be treated, and this will be similar to that of the spectrum equations in Chapter XXIII. The light in which the rotation of the discs was made is the naked arc light, and all the measures were made in that light.

The following is the equation made with the discs :—

$$126 \text{ red} + 144 \text{ green} + 90 \text{ blue} = 79 \text{ white} \qquad \text{(i.)}$$

and the black reflected just 5 per cent. of white light, so that the equation on the right-hand side becomes—

$$79 + 281 \times 0{\cdot}05 \quad \text{or} \quad 93^\circ$$

The composition of the vermilion red was found to

be (in terms of the luminosity of the whole spectrum, and which equalled in area 866 on an empyric scale)—

$$\begin{array}{cccc} \text{RS.} & \text{GS.} & \text{White.} & \\ 142{\cdot}5 & +16{\cdot}5 & +\ 53 & \text{(ii.)} \end{array}$$

the emerald green was—

$$31{\cdot}8 \ +60 \quad +263 \qquad \text{(iii.)}$$

and the blue was $2{\cdot}34 + 1{\cdot}56 + 34{\cdot}2$ (iv.)

Multiplying the equation (i.) by the appropriate factors in (ii.), (iii.), and (iv.), and dividing by 360°, we get—

$$\begin{array}{cccc} \text{RS.} & \text{GS.} & \text{BS.} & \text{White.} \\ 49{\cdot}9 + & 5{\cdot}8 + & 0 & +\ 18{\cdot}55 \\ 12{\cdot}7 + & 24{\cdot}0 + & 0 & +105{\cdot}2 \\ & 0{\cdot}6 + & 0{\cdot}4 + & 8{\cdot}55 \\ 62{\cdot}6 + & 30{\cdot}4 + & 0{\cdot}4 + & 132{\cdot}3 \end{array}$$

Dividing this equation by 866, we get the sensation luminosities for the mixed colours—

$$\begin{array}{ccccc} \text{RS.} & \text{GS.} & \text{BS.} & \text{White.} & \\ 0{\cdot}0725 + & 0{\cdot}0351 + & 0{\cdot}0005 + & 0{\cdot}1527 & = 0{\cdot}2608 \end{array}$$

The ratio of RS. to GS. is 67 to 33, which is closely that obtained from the spectrum equation, so that the above equation derived from the discs may be taken as the normal vision equation.

We do not *need* to refer to the right-hand member of the equation, but if we take it as 93 the luminosity of the white exposed is 93/360 of 1, 0·259.

It will be seen that the luminosities agree to within the third place of decimals, as the left-hand member comes out at 0·2608.

When a colour blind person is tried in the same light, his equation is—

$$210 \text{ red} + 100 \text{ green} + 50 \text{ blue} = 77$$

Taking the luminosities of the red, green, and blue as before, we get, when multiplying them by the equation numbers (ii.), (iii.), and (iv.) $\div$ 360—

$$\overset{\text{RS.}}{91{\cdot}94} + \overset{\text{GS.}}{26{\cdot}6} + \overset{\text{BS.}}{0{\cdot}22} + \overset{\text{White.}}{108{\cdot}7}$$

Dividing by 866, as before, we get—

$$\overset{\text{RS.}}{0{\cdot}1062} + \overset{\text{GS.}}{0{\cdot}0307} - \overset{\text{BS.}}{0{\cdot}00025} + \overset{\text{White.}}{0{\cdot}1253} = \overset{\substack{\text{Total} \\ \text{luminosity.}}}{0{\cdot}2624}$$

RS. is to GS. as 114·2 to 33, the normal equation being as 67 to 33.

The degree of red blindness is given by 67/114·2, or 0·58 RS.

We may now examine the right member of the equation, which is the white in the outer two discs of black and white. It is 77, and, with the light reflected from the black, becomes 91, and 91/360 = 0·2527.

We may now subtract the white of the left-hand member from it, and we get the following equation left :—

$$\overset{\text{RS.}}{0{\cdot}1062x} + \overset{\text{GS.}}{0{\cdot}0307} = \overset{\text{(RB., white).}}{0{\cdot}1274}$$

where x is the RS. factor.

As in the second method of using the spectrum equations for the colour blind, we multiply 0·1274 by $(67x + 33)$, as $(67 + 33)$ is the normal relation of RS. to GS.

This worked out gives $x = 0{\cdot}54$ RS. Another colour blind makes the same equation match with 72 white.

Proceeding in the same manner, we get—

$$\overset{\text{RS.}}{0{\cdot}1062x} + \overset{\text{GS.}}{0{\cdot}0307} = \overset{\text{RS.}}{0{\cdot}0768x} + \overset{\text{GS.}}{0{\cdot}0379}$$

$$x = 0{\cdot}24 \text{ of the normal luminosity}$$

We see, then, that where there is a deficiency in the mixtures due to causes already pointed out, the degree of colour blindness can still be calculated, always supposing that the black and white mixture is to the observer a perfect match to the inner grey given by the discs.

The question of other illumination need not be entered into by examples. They would be carried out in exactly the same manner as that indicated. The use of colour discs to form equations, as before said, has long been known, but the method of using the equations in the manner indicated above is apparently novel.

For general use in forming equations for the colour blind, a yellow light is one that commends itself to the writer. When the light is white, the amount of blue, which is not much more luminous than the black that has to be mixed with the red and green in the inner disc, is so great that the grey produced on rotation is dark. On the other hand, if the white arc light, or, indeed, any other light, is transmitted through a chromate solution as given before, no blue in the inner disc is required to match the outer grey disc. Both the disc and the outside ring are fairly bright, and the matches become easy.

One point must be mentioned which to some extent prevents the disc equations being as useful as the spectrum equations. In the red pigment used, always a certain amount of green sensation is also excited, and in the green a certain quantity of red sensation is excited. It follows that even with an all-red centre the factor of the partially red blind who can make a good match with the outside grey is limited, and any addition of the green disc will not diminish but only increase the proportion of red to green sensation in the centre disc. The same applies to the green blind with the green disc.

A completely red or green blind will, however, match both discs with a grey, since the green or the red sensation will be completely absent to them.

A simple method of arriving at the sector angles at which the different degrees of colour blindness will match a grey, is to place a "chromate" light in the reflected beam of the colour patch apparatus (or in any light which is to be used to illuminate the discs). The discs are then rotated at the colour patch screen, with a white patch alongside. This can be effected as usual with a rod placed in the two beams. The colour of the white is first illuminated by the "chromate" light and a match made with it (see p. 324). The plain red and the plain green are then matched with the single spectrum colour. The red and green discs are then interlaced say, with 30 red and 330 green showing. When the compound disc is rotated, a single colour will match the mixed colour which is noted. By taking more red, another match will be found, and so on. These single spectral colour matches are then applied to Table LVIII., and the degree of colour blindness which they indicate calculated. The different sectors of red and green can then be readily ascertained for any required degree of partial colour blindness.[1]

[1] There will, as stated above, be a limit to the factor.

CHAPTER XXIV

SOME CASES OF UNCOMMON COLOUR BLINDNESS

In this chapter a few recorded cases of colour blindness different to those ordinarily found are given, and to most the method of ascertaining the amount of colour blindness has been applied.

Cases of Monochromatic Vision.

The first is a type of colour blindness in which all sense of colour is lost. Reds, greens, blues, yellows, and, in fact, all colours can be matched with one another, they all being different shades of grey to this type of colour blind. This type of colour blindness is congenital; at least it was said to be so in the few cases examined. Both eyes were similarly affected. It is usually supposed that this monochromatic vision is due to some form of disease, but it seems to be, if not hereditary, at all events found in the same generation of a family. Two cases, which we call P. and Q., are examples (Fig. 91). They were brothers, and had identical lack of colour perception. Their luminosity curves are valuable, as they practically coincide with the luminosity curve of a feeble spectrum, which is given in Chapter VIII., showing that in the feeble spectrum the luminosity is principally due to the fundamental sensation of light in normal vision. The figure shows the luminosity of the spectrum to P., and also the

extinction of light measures that he made. The intensity to the normal eye of the D light was equal to one candle at 1 foot distance from the screen. In the table which follows, the readings in column IV. are in millionths of the original intensity. In column V. we have P.'s persistency curve, with a maximum of 100. Column VI. is the luminosity curve taken direct. It will be noticed in comparing these two curves, that the readings in the blue-green, blue, and violet are smaller in the luminosity curve than in the persistency curve. This no doubt is due to the fact that the luminosity curve was taken when the images of the patches fell on the yellow spot, whilst in the extinction curve the eye was allowed to wander when looking for extinctions, and is to be collated with the results given in Tables XVII. and XVIII. for the normal eye.

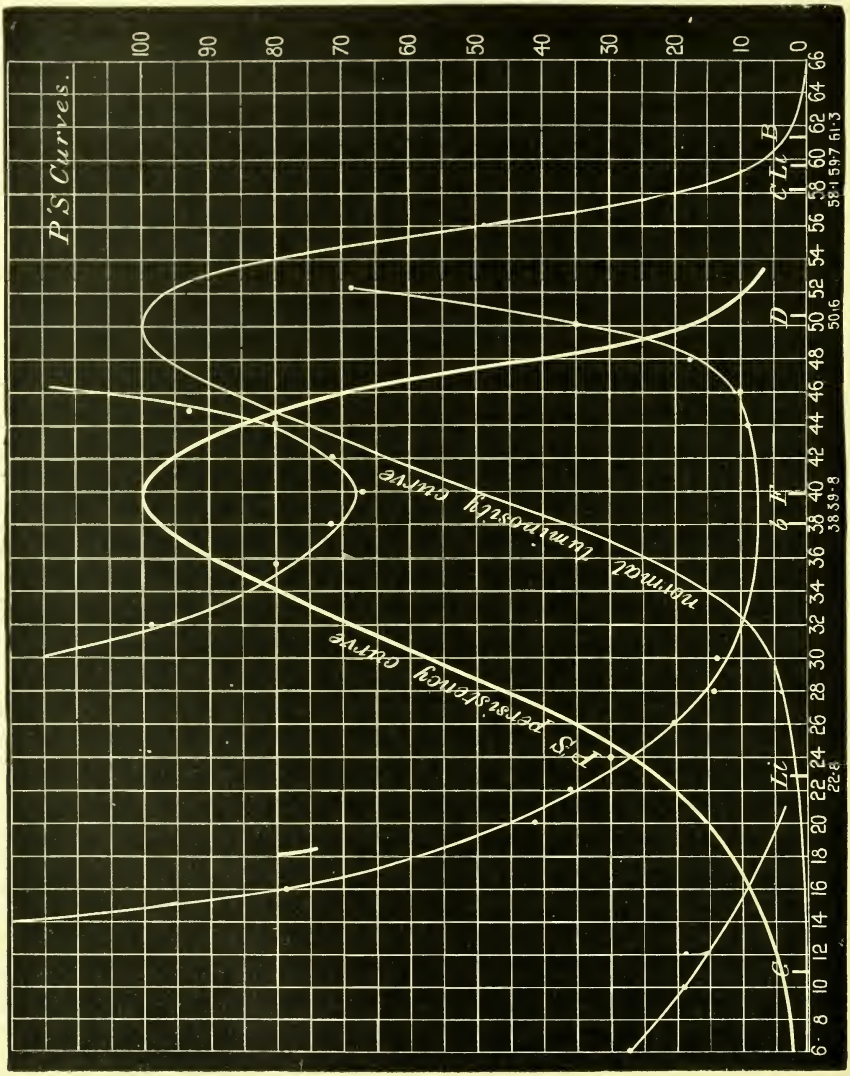
If we multiply column VI. by IV., we get the value of the extinction when the rays are made of equal luminosity. As far as the blue-green they have equal values (about), but diminish from the blue-green to the violet, due to the cause to which attention has just been called. It thus appears that P. has only one sensation, that of light, since the extinction value of every ray when of equal luminosity is, more than probably, the same.[1] From other evidence it appears that P. and Q.'s sensation of luminosity for total white is about $\frac{1}{30}$ of the normal.

As cases of monochromatic vision are rare, the following one is also put on record.[2] The patient, whom we will call K. B., was kindly brought by Mr. Parker. He was

[1] If the method of ascertaining the amount of colour blindness for red or green be applied to these curves, they will be found to give impossible factors.

[2] Paper No. 16.

aged twenty-five at the time when examined for colour vision. The notes of his case were as follow :—" Vision



always defective; has always been colour blind. Has quick horizontal nystagmus; probably an absolute cen-

tral scotoma. He is always 'day-blind.' His vision for right and left eyes is 6/60. He is not night-blind. His fields are nearly, but not quite, full for white. He shows no definite changes in his eyes."

TABLE LIX.—*P.'s Luminosity and Extinction Curves.*

I.	II.	III.	IV.	V.	VI.
Scale No.	Wave-lengths.	Mean reading of extinction in millionths of original luminosity.	Adopted reading in millionths of original luminosity.	Persistency curve 680 ad. reading.	P.'s luminosity curve.
52	5996	68	68	10	7
50	5850	35	35	19·4	19
48	5720	17	17	40	39
46	5596	10·2	10	68	65
45	5538	9·3	9	76	76
44	5481	8	8·1	84	90
42	5373	7·2	7·2	94·5	98
40	5270	6·7	6·8	100	99
38	5172	7·2	7	97	97·5
36	5085	8·05	7·7	90	90
34	5002	8·05	8·4	81	80
32	4924	9·9	9·8	69	65
30	4848	13·2	12·5	54	50
28	4776	13·9	15	45·3	36
27	4742	16·8	17	40	31·5
26	4707	21·6	20·5	32	26·5
24	4639	30	27	25	19·5
22	4578	36	35	19	14
20	4517	42	45	15·5	10
16	4404	79	79	8·5	5·5
10	4245	180	190	3·6	2·5
6	4151	270	270	2·7	...

In taking his luminosity curve, he matched all colours with white with the same facility as if they were white, though he was not a good observer at first. The following table gives the luminosity of the spectrum to him, and for the convenience of reference P.'s curve of luminosity is given for comparison :—

TABLE LX.

Scale of spectrum (prismatic).	K. B.'s luminosity.	P.'s luminosity.	Scale of spectrum (prismatic).	K. B.'s luminosity.	P.'s luminosity.
56	2·5	—	32	61·5	65
54	9	—	30	43	50
52	16	7	28	37	36
50	27·5	19	26	30	26·5
48	42·5	39	24	24	19·5
46	61	65	22	18·5	14
44	82·5	85	20	14·5	10
42	96	98	18	11·5	—
40	100	99	16	9	5·5
38	95·5	97·5	14	7	—
36	87·5	90	12	5	—
34	75	80	10	3	2·5

It will be remarked that the maximum of each curve is about scale number 40, or close to E. On the red side of the maximum the curves do not absolutely agree. K. B.'s observations were first made in the red and green, and his readings at first were not very close, and a mean had to be taken. As the colours he had measured went towards the blue, his measures were much more accordant, as he had become accustomed to the methods employed. The slight divergence on the left-hand side of the curve from that of P. is probably due to the colouring matter in his yellow spot. Attention must be again called to the fact that both P.'s and K. B.'s curves are practically identical with those obtained by the normal eye when it measures a spectrum of very feeble luminosity, and also agree with the results obtained by measuring the diminution of each ray when it first becomes invisible, and making a curve of the reciprocals of the numbers, taking the highest point of it as 100.

A Case of Colour Blindness and Lack of Pigment.

A case[1] is now given in which the absorption by the yellow spot pigment seems to be absent, coupled with a considerable amount of red blindness. This was a remarkable case, which Mr. Nettleship mentioned.[2] He had stated that this lady, N. W., mistook blue for red, and it was with some curiosity that this case was examined. Her first examination was as to colour sense with the spectrum colours, a patch of monochromatic light being placed in juxtaposition with an equal patch of white light. At 62·5 (λ 6890) of the scale the red of the spectrum disappeared. As the slit moved along the spectrum, and the white was approximately reduced to equal luminosity, she described all the red as grey, and of the same colour as the white until 53·5 (λ 6110), and after this point she said the colour was brownish compared with the white. The colour continued of this hue to her till 48 on the scale (λ 5720), when she said the colour was neither brown nor green, but both. From 48 on the scale she described the colour as green till it sharply ended at 31·5 (λ 4905). In the blue she again began to see grey; the grey at this end of the spectrum, and also of the white patch, she called brownish grey. [This name must evidently have been a mental distinction, as she described the red end and the white as grey only, and not brown-grey; and, indeed, she was tried again over that part of the spectrum, and adhered to the previous naming. It would appear to be due to the low luminosity which made the grey appear brownish to her, and not to any actual difference in hue.]

[1] Paper No. 17.

[2] To a Committee of the Royal Society on Colour Vision which was sitting at that time.

Her curve of luminosity in the spectrum was next taken, and her readings are given in the table. The curve is shown in Fig. 94. The shaded band beneath it applies to her curve.

TABLE LXI.—*Showing N W.'s Curves.*

I.	II.	III.	IV.	V.	VI.
Standard Scale Nos. (SSN.).	λ.	N. W.'s Luminosity.	N. W.'s Luminosity ×0·5.	Luminosity from Table LIV., RS. being 0·25 of Normal.	N. W. named the prismatic colours against white.
62·5	7020	0	0	0	Both grey
60	6728	3	1·5	1·75	,,
58	6521	10	5	5·4	,,
56	6330	30	15	14·2	,,
54	6152	52	26	25·7	Colour brownish, white grey
52	5996	70	35	35·6	,, ,, ,,
50	5850	81	40·5	43·7	,, ,, ,,
48	5720	87	43·5	48·1	Colour brownish-green, white grey
46	5596	90	45	46·3	Colour green, white grey
44	5481	88	44	41·8	,, ,, ,,
42	5373	72	36	36·5	,, ,, ,,
40	5270	62·5	31·2	30·5	,, ,, ,,
38	5172	46	23	22·9	,, ,, ,,
35	5085	23	11·5	12·4	,, ,, ,,
32	5002	12·5	6·25	5·67	,, ,, ,,
31	4885	10	5	4·67	Colour brownish-grey, white brownish-green
25	4675	5	2·5	1·41	
20	4517	3	1·5	·52	,, ,, ,,
15	4377	2·5	1·25	·28	,, ,, ,,
10	4245	1·5	·75	·16	,, ,, ,,
0	4010	·2	·1	·014	,, ,, ,,

The table shows that the readings near the maximum were a little erratic, probably owing to the fact that at that part green was distinguished, the rest of the spectrum being grey or brownish grey to N. W., and they therefore presented no difficulty in comparison with the white beam. Using rays on each side of the maximum

to form the equations, the factors of reduction of the curve to compare it with the normal curve are obtained. Taking SSN.'s 56 and 40, we form the first pair of

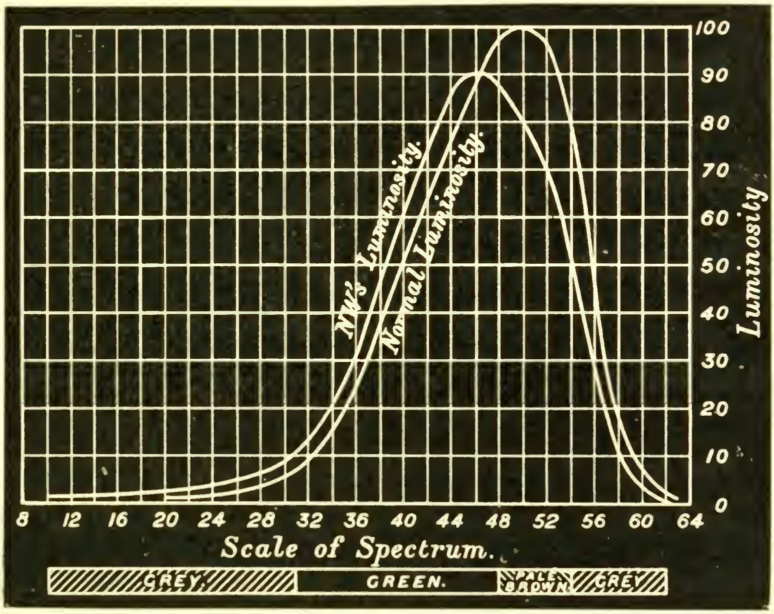


FIG. 94.

equations from the luminosities in Table LIV. and that of N. W.'s luminosities. As before, the right hand of the equations are formed from the RS. numbers in Table LIV.—

$$50 - 30z = 47{\cdot}7y \qquad 50 - 62{\cdot}5 = 25{\cdot}8y$$

This gives—

$$y = 0{\cdot}73 \qquad z = 0{\cdot}51$$

Another pair of equations can be formed from SSN.'s 54 and 44—

$$80 - 52z = 72{\cdot}4y \qquad 75 - 88z = 31{\cdot}3y$$

which give—

$$y = 0{\cdot}69 \qquad z = 0{\cdot}56$$

From SSN.'s 52 and 42 we get—

$$96 - 70z = 80{\cdot}6y \qquad 62{\cdot}5 - 72z = 34{\cdot}6y$$

which make—

$$y = 0{\cdot}74 \qquad z = 0{\cdot}52$$

From SSN.'s 58 and 46 we get—

$$21 - 10z = 20{\cdot}8y \qquad 87 - 90z = 54{\cdot}2y$$

which make—

$$y = 0{\cdot}77 \qquad z = 0{\cdot}5$$

From SSN.'s 60 and 38 we get—

$$7 - 3z = 7y \qquad 36 - 46z = 17{\cdot}5y$$

which make—

$$y = 0{\cdot}78 \qquad z = 0{\cdot}57$$

The mean of the different values of y is . . 0·74

And that of the different values of z is . . 0·53

For the sake of simplicity, we may take the values as $y = 0{\cdot}75$, that is, x (the red sensation) is 0·25 of the normal, $z = 0{\cdot}50$. In Table LXI. these values are employed. Column V. gives the theoretical curve derived from Table LIV. containing the colour equations.

Comparing columns IV. and V. together, we see that at the position of maximum luminosity the theoretical values differ from those obtained from the readings,[1] the mean of which was taken. A further examination of these two columns also shows that at the violet end of the spectrum the luminosity values obtained by N. W. are much larger than given in the normal curves.

The luminosity of the blue sensation is very small

[1] Had the evidently low readings been omitted when calculating the mean luminosity value, the two would have tallied well.

compared with the luminosities of the red and green, and is negligible as far (say) as SSN. 40, but from SSN. 25 to the violet end of the spectrum the luminosity of the blue sensation plays a larger and larger part in the total luminosity of each scale number.

We have already found the factor of the red sensation (which we see from the table forms part of the normal violet). If, then, from the luminosity values obtained in this region of the spectrum by N. W., we subtract her red sensation, and also her green sensation, the residue will be due to the blue sensation, which can be compared with that existing in the writer's vision within the yellow spot.

Taking her readings from SSN.'s 25 to 0, we obtain the following result :—

Table LXII.

SSN.	N. W.'s Luminosity.	N. W.'s Reduced Red Sensation.	GS.	N. W.'s BS.	Normal BS.	N. W.'s BS. / Normal BS.
0	·1	·014	...	·086	·022	4
10	·75	·06	...	·64	·1	6·4
15	1·25	·11	...	1·14	·16	7
20	1·5	·2	·1	1·25	·234	5·8
25	2·5	·32	·84	1·34	·25	5·4

If we lay down the luminosities shown in a curve, and draw a freehand curve between the points, we get $0 = 0{\cdot}15$, $10 = 0{\cdot}7$, $15 = 1{\cdot}1$, $20 = 1{\cdot}65$, $25 = 2{\cdot}6$ as ordinates, and the resulting ordinates of N. W.'s blue sensations are six times larger than those of the normal curve. This gives a very good clue[1] to her naming the colours of the spectrum as given.

[1] With a normal eye fatigued by red to produce ·25 RS., particularly with an excess of blue sensation, the colours seen would not be far different from those of N. W. See Chapter XXV.

An endeavour was made to form a series of colour equations with her eyesight by placing three slits in different parts of the spectrum, but without success, although a match with white was made in two positions. One slit was placed in the orange red at about 52 (λ 6000) of the scale, another at E, and the third at G, and white light was formed, though her match was so erratic that it was useless to measure the apertures. When the slit in the violet was covered up, a white patch being alongside as a comparison, she called the mixture of red and green "brownish green"; when the slit in the red was covered she called the mixed light of green and violet "green"; and when the green slit was covered up she called the purple colour a "different kind of brown."

When the first slit was moved into the red near the lithium line she called the colours "green," whenever the green slit was uncovered. A piece of signal-red glass of the London, Brighton, and South Coast Railway was placed in the white reflected beam, forming a red patch, and a patch of the blue scale at No. 30·5 (λ 4862) was placed alongside, and she matched them in luminosity and in colour. (The dominant colour of the signal glass in question was λ 6220.) She finally was tested with colour discs:[1]—

One being red with dominant wave-length (R)	λ 6150
Another, emerald-green (G) ,, ,, .	λ 5373
And the third, French ultramarine (U) ,, .	λ 4700

To make white she required—

130 G + 113 R + 117 U = 72 W + 288 B. (Black corrected for white light reflected.)

[1] The colours of the discs were all impure colours, and each colour stimulated all three sensations more or less. A reference to Chapter XVI. will show how it was that the discs matches could be made. Chapter XXIII. should also be studied in connection with them.

She was then tried with the blue and green discs alone, and made a match—

$$258\ U + 102\ G = 65\ W + 295\ B \text{ (corrected).}$$

An attempt was made to match with the green and red discs alone, but this failed.

She matched the red disc alone with black and white, and also the blue disc alone—

$$360\ R = 56\ W + 304\ B \text{ (corrected),}$$

$$360\ U = 60\ W + 300\ B \text{ (corrected).}$$

With any proportion of R and U mixed together she matched a grey of approximately the same intensity as above, as it might be supposed she would from the last two equations.

A Case of Colour Blindness with Great Excess of Pigment.[1]

The next case (M.) is one in which the amount of pigment in the retina is so great that it practically cut off a large portion of the blue end of the spectrum. M. was examined more than twenty years ago by the author, when the sensation curves had not been worked out. It was believed at the time to be a case of violet blindness. His description of spectrum colours was most remarkable. He only saw two colours, red and black. He called all green and blue, black; green, however, he called bright black, blue being darker black; yellow he called white. At SSN. 52 on the scale he saw a "little red," at SSN. 50 "no colour"; his neutral point where he saw the spectrum colourless would be about 49·5, or about λ 5800.

His luminosity curve is given in the following table:—

[1] Paper No. 4.

TABLE LXIII.

Scale Number.	Wave-length.	Mean Reading.
61	6839	2
59	6621	7
57	6423	18
55	6242	36
53	6074	49
52	5996	52
51	5919	54
50	5850	54
49	5782	52·5
48	5720	50
47	5658	46
46	5546	41
44	5481	32
42	5373	23
40	5270	17
38	5172	10
36	5085	4
34	5002	1
31	4885	·5
28	4776	0

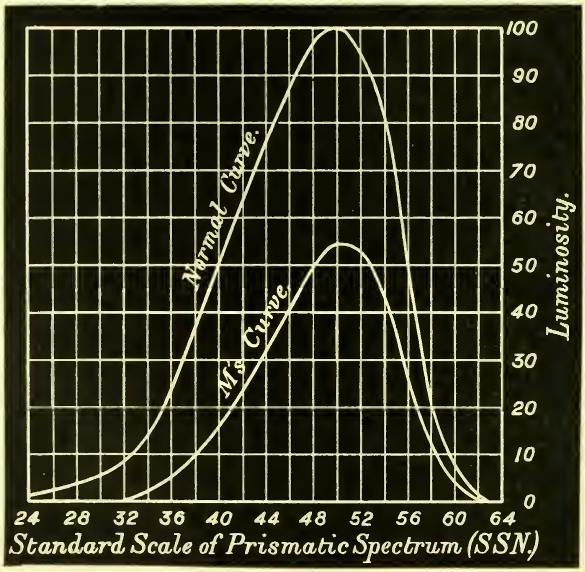


FIG. 95.

Taking SSN.'s 52 and 46, we get, according to the first method in the last chapter,—

$$96 - 52z = 15{\cdot}36y$$

$$87 - 41z = 32{\cdot}7y$$

$$y = {\cdot}54 \text{ ; that is, M. has } {\cdot}46 \text{ GS.}$$

Taking SSN.'s 56 and 44—

$$50 - 27z = 2{\cdot}25y$$

$$75 - 32z = 30{\cdot}8$$

$$y = {\cdot}56, \text{ or M. has } {\cdot}44 \text{ GS.}$$

Finally, taking SSN.'s 54 and 42—

$$80 - 42{\cdot}5z = 7{\cdot}6y$$

$$62{\cdot}5 - 23z = 27{\cdot}75y$$

$$y = {\cdot}62, \text{ or M. has } {\cdot}38 \text{ GS.}$$

On considering the whole curve, and where the absorption due to pigment may commence, we shall not be far wrong if we make M. to have ·46 to ·5 GS. The curves of a ·46 GS. would lie closely on that of M. on the red side of the maximum and the absorption would begin to show at SSN. 46. The extinction curve of M., which was rather erratic, shows that that part of the curve in the red resembles that of a normal eye, but in the parts where the absorption is powerful the normal eye shows the fundamental light as at least 180 times greater than M.'s.

Case of White Sensation only to one Eye, whilst Normal to the other Eye.[1]

Miss W. was brought to the laboratory by Dr. Lindsay Johnson. The right eye was apparently normal for colour, but with the other she saw nothing but shades of white.

[1] Paper No. 17.

Miss W., it appears, has had a slight stroke of paralysis, which affected her left side, and subsequently she discovered that colour sensation in the left eye had disappeared. The cause, from an examination by a specialist, seemed to be atrophy of the optic nerve.

She was examined with the spectrum colours, and her left eye found to be totally blind to every colour, though her perception of light was fair. She had very little difficulty in comparing the luminosity of the most brilliant spectrum colours with the white patch of light placed alongside them. In making the measurements she experienced a certain amount of fatigue, but, by resting the eye for short intervals, her readings were very constant. The following is the table of her readings :—

Table LXIV.

Scale No.	Wave-length.	Readings.	Remarks by Miss W.
63	7082	0	Both colour and white patch appeared as white throughout the spectrum.
62	6957	1	
60	6728	7	
58	6520	18	
57	6423	28	
56	6330	43	
54	6152	76	
52	5996	90	
50	5850	95	
48	5720	93	
46	5596	83	
44	5481	71	
42	5321	58	
40	5270	46	
38	5172	32	
36	5085	21	
34	5002	12·5	
32	4924	7	
30	4848	4·5	
28	4776	3	
25	4675	1·5	
20	4518	0·4	
19	4488	0	

At 19 the light perception was so diminished that she could not match the grey. Her light perception extended further into the violet (as white) beyond this point, as the subsequent measures of her extinction of light showed conclusively.

The orange sodium light of the spectrum was thrown on the apparatus therein described, of a luminosity of an amyl lamp 1 foot off, and the slit giving this brightness remained unchanged throughout the examination, and was moved through the spectrum till a position was reached where all light was just extinguished. Her perception of the point of extinction was very acute. Rotating sectors were placed in front of the apparatus, set at different angles, so that the amount of reduction of the luminosity of the spectrum was known at once.

Table LXV.—*Scale Readings of Light Extinction.*

Light coming through the slit reduced to—	Slit moved towards the violet.	Slit moved towards the red.
No reduction.	15	53·7
$\frac{1}{2}$ intensity.	20·7	52·4
$\frac{1}{4}$,,	21·7	50·9
$\frac{1}{9}$,,	23·2	48·7
$\frac{1}{18}$,,	26·7	46·7
$\frac{1}{36}$,,	34·7	44·2
$\frac{1}{45}$,,	—	40

The extinction of light with the full aperture to the writer was with the size of the patch employed at 57·9. At 57·9 the luminosity of the spectrum is 0·22 that at the D line, and as the light on the screen at the end

of aperture was 1/620 that falling on the instrument originally, it follows that the extinction to a normal eye when the light of 57·9 (λ 6510) was 0·22/620 or 0·000355 of an amyl lamp placed at 1 foot from the screen.

At D, if 71/100,000 of an amyl lamp illuminated a screen 1 foot off, it is invisible to Miss W. With normal vision, if the screen be illuminated with 7/100,000 of the same light, it just becomes invisible. She has therefore about 1/10 of the light of normal vision in the colour blind eye.

A Probable Case of Monochromatic Vision.

About July 1892, a case of colour blindness quite unusual was examined by the author and published by the Royal Society.[1] B. C., as he was called in the paper, was then a youth of nineteen, who had been serving at sea. His form vision was perfect, and he was not night blind, though he stated that on a cloudy day his vision seemed to be more acute than in sunshine. There is reason to believe that some of his ancestors were colour deficient. Being tested with the wool test (see Chapter XXVI.), he matched all colours with one another. He called the lighter colours "dirty" or "pale" blue, terms which were found to be synonymous. In the spectrum he called every colour blue except the bright yellow, which he called white; but when the luminosity of the colour was reduced, he pronounced it a good blue. So with white, he called it white when bright, but as its luminosity was reduced it passed through the stage of "dirty blue" to full blue.

[1] Paper No. 4.

Testing him with colour discs (see Chapter XI.) he made the following matches :—

360 red matched in brightness and colour . .	315 black + 45 white.
360 green matched in brightness and colour . .	258 black + 102 white.
360 blue matched in brightness and colour . .	305 black + 55 white.

With these proportions he emphatically stated that all were good blues, and that the inner disc and outer ring were identical in brightness and colour.

The luminosities of the red and green to the normal eye are not very different. The equation of red and green shows that the green is much brighter to B. C. than the red or the blue. Further, it must be remembered that the red contains a considerable percentage of green sensation and the blue a large quantity of green sensation and also some red; whilst the green also has more than half of red sensation (see Chapter XVI.). As B. C. only saw one colour, it seemed likely that the one sensation he felt was the green. The white, of course, would appear green, and is quite independent of the name he gave it. His curve of luminosity is a remarkable one, and is given in Table LXVI., and is shown in the figure. A great falling off in the luminosity when compared with that measured by the normal eye will be noticed both in the red and the blue of the spectrum, and, as before said, it seemed probable that his chief colour sensation was the green.

The luminosity of a spectrum to his eyes was measured with some difficulty at first, but afterwards, when the terms " dirty " or " pale blue " applied to a colour had been

explained by the disc experiments, the measures were made with some degree of accuracy. The method

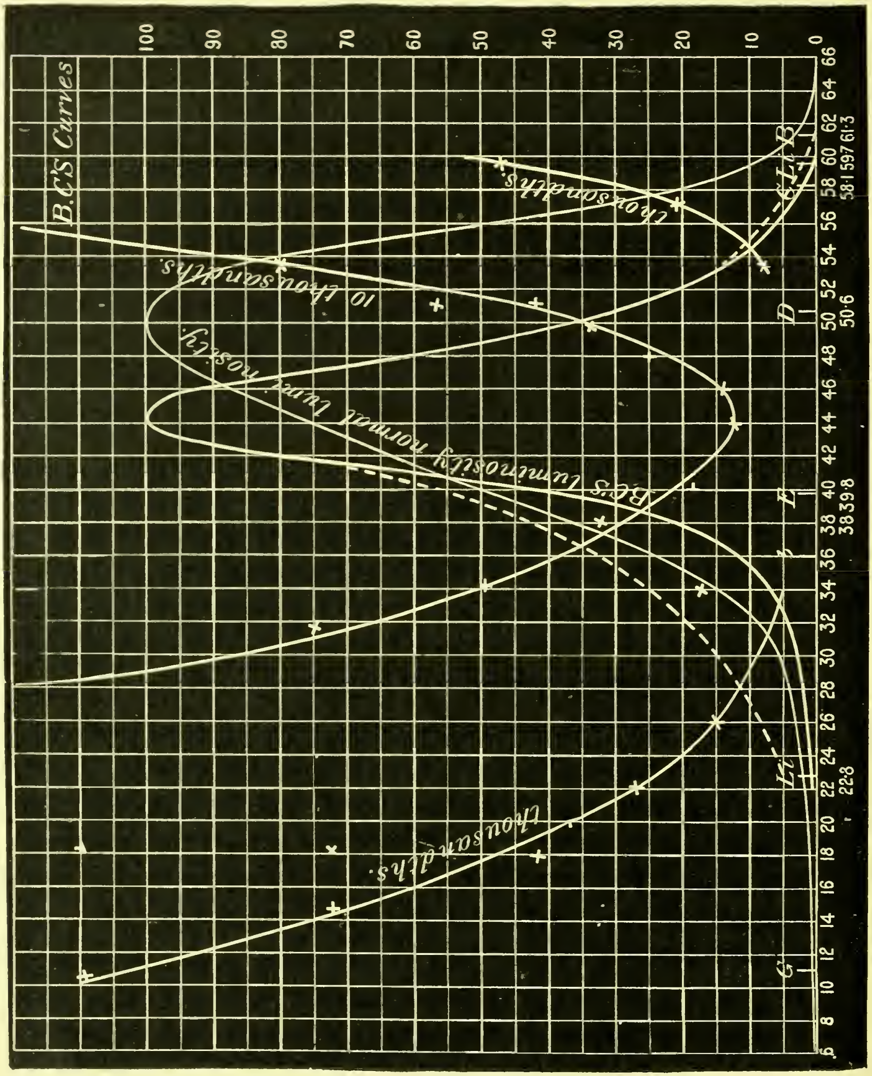


Fig. 96.

adopted was to diminish the white light illuminating one shadow in the colour patch (see Chapter VIII.) to a point

which made it appear a good "blue" to him, when a slight alteration in the intensity was sufficient to secure equality of luminosity between the white and the colour.

TABLE LXVI.—*B. C.'s Luminosity and Extinction.*

I.	II.	III.	IV.	V.	VI.
SSN.	λ	Adopted Readings of Extinction in $\frac{1}{100000}$	Persistency Curve. Maximum 100.	Luminosity.	Comparative Luminosity of Extinction when each Ray Extinguished is of Equal Luminosity.
60	6728	5500	2·3	·5	27·5
58	6520	2800	4·5	2	56
56	6330	1500	8·3	6	90
54	6152	950	13·1	11·5	109·2
52	5996	580	21·6	21·5	125
50	5850	350	36	37	129·5
48	5720	215	58	60	129
46	5596	140	89·3	92	129
44	5481	125	100	100	125
42	5373	150	83	85	127·5
40	5270	215	59	45	96·7
38	5172	290	43	21·5	72·3
36	5055	380	33	11·5	43·7
34	5002	500	25	7	35
32	4994	650	19	4	26
30	4848	850	14	2·5	23·3
28	4776	1100	11·4	2	22
26	4707	1500	8·3	1·5	22
24	4639	2000	6·2	1	20
22	4578	2700	4·6	·5	13·5
20	4750	4750	...	...	...

Treating the curve of B. C. as we treated that of M. and N. W., we find that it answers very fairly to the green sensation curve. Any small divergence from it is probably due to the errors of observation by an untrained

observer. The highest factor of deficiency obtained is 1·2 and the lowest ·95 for the red sensation. The first is of course impossible, but a mean of all the factors thus obtained is closely unity, which shows that he possesses no red sensation.

A further test of his colour sensation was made by taking the extinction of the various rays of the spectrum. His observations were fair except on the violet side of the F line where they became slightly erratic, but by requesting him to use the whole retina to obtain the last glimpse of light, a very concordant curve resulted.

In the figure the extinction of the various places in the spectrum are indicated by ×, and the extinction has been taken from the freehand curve drawn as nearly as possible through the several points.

When the "persistency curve" was made, it agreed closely in the green and yellow with the luminosity curve, which stopped when not far in the blue.[1] As the whole retina was employed in the extinction observations, it indicates that the falling off of luminosity in the blue part of the curve is not due to excessive pigmentation in the yellow spot, and seems to point to an absence, *total* or *nearly total*, of the sensation of light (in contradistinction to colour). If we turn to Table XIII., col. IV., page 150, we shall find that at SSN. 44 the extinction of colour to a normal eye takes place when it is ·0027 of the luminosity of the ray when D is 1 candle at 1 foot distant from the screen. In Table LXVI. it is shown that B. C. loses all sensation of light when the same ray under the same conditions is reduced to ·00125. This last is of the same "order" as the first. If this is a case of monochromatic vision, it is quite a different kind to that recorded for P. and Q., since their place of maximum

[1] The deviations of the persistency curve is shown by the dotted line.

luminosity differs largely from that of B. C. It appears that whilst the former only have the sensation of light and not that of colour, B. C. appears to have the sensation of green and probably the absence of the sensation of light.

CHAPTER XXV

ON COLOUR FATIGUE

We will next consider if the results of fatigue of the retina by different colours bears out or disproves the trichromatic theory.

After Images.

In its simplest and qualitative form fatigue is shown when an eye steadily gazes at a spot of colour on a black ground. When the eye is then turned to a grey paper, an image of the spot will show itself, and travel over the paper as the eye moves, and will be of a colour complementary to the real colour of the spot. When it is a red spot that is looked at, the after image of the spot on the grey paper will be a bluish green, though pale. If it be an emerald green spot, the image on the grey paper will be pink, and so on. The explanation is perfectly simple. When the red spot has been steadily looked at, its image falls on a small portion of the retina and principally acts on the red receiving apparatus. If colour vision be connected with the chemical decomposition of some red, green, and blue sensitive substance, then the prolonged gaze decomposes a certain quantity, mostly of the red, and the sensitiveness to red becomes less and less. When the eye is turned to the grey paper (degraded white), the light from this ordinarily would stimulate each of the

three receiving apparatus equally. The red apparatus not having recovered the full sensitiveness in the spot on the retina on which the red image fell, it follows that the green and the blue are stimulated much more than the red. As the red sensation only acts partially on the red fatigue spot on the retina, the after image seen on the grey paper is a pale blue-green image. For similar reasons, when other coloured spots are made to fatigue a a spot in the retina, we have the complementary colour when looking at the grey.

With the colour patch apparatus we can study fatigue qualitatively and quantitatively in a very simple manner. We can place a patch of white light on a small square surface, and fatigue the whole of the retina by looking at the surface of the prism through one or other of the slits, placed in the various colours. Closing one eye and looking at the red ray with the other, fatigue is induced in the latter. On looking at the white patch, it will be found to take the complementary colour to the red, viz. bluish green ; the brighter the light seen on the surface of the prism, the less pale the blue-green will appear. Using the unfatigued eye, it will be seen that the white is unchanged.

By using a second square on which to receive light, a patch of blue-green light mixed with a varying amount of white can be arranged. By use of a kind of stereoscopic arrangement, which we describe later, the white patch can be viewed by the fatigued eye, and the colour by the unfatigued eye, and after a few trials the two can be made to match. Instead of the white on one patch, we can place, say, a greenish yellow near the D line about SSN. 48·7. At this point the two sensations of red and green, according to the writer's measures, are equally stimulated—that is to say, it is the place where

the red and green sensation curves cut when made of equal areas. If the trichromatic theory holds good, an eye fatigued by the red should show this colour as no longer yellowish, but decidedly greener; and if fatigued by the green, decidedly redder. When this experiment is carried out, the results are those to be anticipated. By throwing a greenish patch upon the second square from a second spectrum, the green can be matched, as is shown later on. In the same way other colours can be examined, and in all cases the confirmation of the trichromatic theory seems to be complete.

The reverse operation can be carried out: the fatigue may be made by the colour which is to be examined. Take the ray at SSN. 48·7 and fatigue one eye with it, and then see the effect it has upon a pure red patch. It will be found that the red has lost considerable luminosity, which can be verified by observing immediately afterwards the patch with the unfatigued eye. It has been suggested that there is a sympathetic action between the two eyes, but these experiments and others leave no doubt that the sympathetic action is not recognisable. Using the stereoscopic arrangement described later, the luminosity of a red patch placed next that observed by the fatigued eye, can be matched by it in luminosity. When the patch caused by the green ray at (say) SSN. 37·5 is observed with the fatigued eye, it will be found to be of diminished luminosity and to have a slightly more bluish tint than it is to the unfatigued eye, which is again what would be predicted from the trichromatic theory. The fatigue may also be caused by a prolonged gaze at a patch of colour. The general results that are obtained from these fatigue experiments in the spectrum are as follows. When the eye is fatigued by red, the red itself is reduced in lumi-

nosity; the orange becomes yellow, the yellow greener; whilst the green, owing to the inherent white, becomes a bluer green; the blue-green is not so much affected; the blue becomes greener and the violet becomes bluer.

When the eye is fatigued by green, the red remains unaltered; the orange becomes redder, as does the yellow; the green becomes paler, and at one part nearly white; the blue-green becomes bluer, the blue more violet, and the violet unchanged.

Fatigue by a patch of blue is more difficult to induce. The principal change is in the blue-green, which becomes greener, and the violet redder. As the blue ray which answers best to the blue sensation is mixed with some 80 per cent. of white, and is only feebly luminous, it is not hard to understand the feeble nature of the fatigue which is induced. In reference to the fatigue produced by the white, it is only necessary to advert to an experiment with a white wafer on a ground of black velvet. When steadily gazed at by the eye, which is then turned to a grey surface, it will be found that the image of the white spot will appear darker than the grey.

Fatigue by Extremely Bright Colours.

Coming next to fatigue by more intense colours, we must refer the reader to the most suggestive paper by Dr. Burch[1] on "Artificial Temporary Colour Blindness." By fatiguing the retina with extremely bright colours, complete temporary colour blindness was apparently induced. In order to get red fatigue, he employed a burning-glass of 2 inch focus, placed at such a distance from the eye that the pupil was filled with direct rays of the sun after passing through ruby glass backed with

[1] *Phil. Trans.*, Series B., vol. cxci. (1899), pp. 1-34.

a magenta-stained film. For green fatigue he employed three thicknesses of green glass coloured with cupric oxide; and a tank filled with an ammonio-sulphate of copper served to give violet fatigue (Dr. Burch came to the conclusion that his vision required a fourth sensation of violet).[1] For blue fatigue he reverted to the blue of the prismatic spectrum. By fatiguing the retina for a sufficient time with these different colours he became completely red, green, blue, or violet blind, and describes what effect such colour blindness had on the colour of objects. So far as the red and green sensations are concerned, it appears that the effect produced is that experienced by the eye which is congenitally totally blind to one or other of these sensations. In the next pages it is not proposed to show the result of extreme fatigue of the retina, but only of fatigue sufficient to show that incomplete colour blindness can be imitated by it in an eye of normal vision.

Use of a Stereoscope.

For use in the above and subsequent investigations of the effect of retinal fatigue by the different colours of the spectrum, a special arrangement had to be made for viewing the white or the colour with the fatigued eye, and at the same time any other colour with the unfatigued eye. It was also convenient that the colour which was to be the fatiguing colour should be brought to the place which the eye would occupy when viewing the coloured or white patch.

Fig. 97 will show the arrangement. A and B are slits in the double spectrum apparatus (see p. 44) with the collecting lenses L and L′ *in situ* to throw patches of

[1] "The sensation which in this book is called the blue sensation seems to be intermediate between Dr. Burch's blue and violet."

any desired colours on the different white screens C and D. (If a white on the screen D is required, the slit B is removed and the whole spectrum is collected by L′. The luminosity of the white can be reduced by sectors or other means.) K is a thin screen pointing as shown, so that its direction, if produced, would divide the distance between C and D equally. E′ and E″ mark the position the eyes occupy. For the sake of comfort, the forehead rests on a pad fixed to K. With this

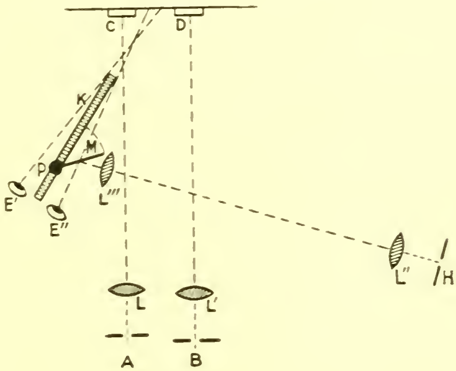


FIG. 97.

arrangement the right eye sees the patch D only, and the left eye the patch C only. This arrangement is made for use when the right eye is to be fatigued.

To bring the fatiguing ray to the eye, a third spectrum with a movable slit is formed at H by utilising the reflected beam of the colour patch apparatus (which is ordinarily employed as a comparison white light) to form a spectrum with a second set of prisms. The ray from this spectrum, coming through a slit, passes through a lens L″, and falls on a mirror M.[1] The mirror M is

[1] The use of the mirror was suggested by Dr. Watson, to allow the head and eyes to remain in one position during the whole of one observation.

pivotted at P, and can be brought against K, leaving an uninterrupted view by the right eye of D. The lens L‴ is inserted in the beam so that the whole of the pupil may be fatigued.

Should it be desired to have a less intense light for the fatigue, a white surface can be substituted for the silvered mirror, a colour patch being formed on it. To use the apparatus, the eyes are placed in position, and the distance apart of the C and D is so arranged that the patches of colour appear to touch. When it is desired that the same colour shall be in both patches, the Scale Nos. of A and B being known, this can be easily done and a confirmation of the correctness be made by making C and D overlap and placing a rod in the path of the beams, using unfatigued eyes to form a judgment. The slits in each can be so adjusted that the two patches are equally bright.

Qualitative Observations.

The first experiments carried out were qualitative, with the fatigue in the right eye induced by the colour patch at M. Patches equally bright were thrown on C and D with unfatigued eyes. The two eyes were then placed in position, and the right eye fatigued by gazing at the colour patch on M for 30 seconds. A twist given to P uncovered D and the effect on the colour noted. The following are the notes of the qualitative observations, both patches remaining unaltered.

The luminosity of the "fatiguing" patch was about 2 candles 1 foot from the screen. The changes noted are when the fatigued eye is compared with the unfatigued.

TABLE LXVII.

SSN.	Red Fatigue.	Fatigue with SSN. 50·6 (D).	Fatigue with SSN. 42·8.
59·8	Same colour, but darker	No change; a little darker	A little darker
57·6	,, ,, ,, ,,	Colour a little darker	,, ,,
50·6	Greener and slightly darker	No change, only darker	Slightly darker
42·8	Green; slightly bluer	Bluer and darker	Darker; no change in colour
37·5	,, ,, ,,	Much bluer and rather darker	Slightly bluer
31·2	No perceptible change	Slightly bluer	Bluer and darker
16·5	Bluer than unfatigued	No apparent change in colour, but darker	No visible change in colour
All the violet	Much bluer and darker	Bluer and darker	Slightly dimmer

Percentage Composition of Spectrum Colours in terms of Equal Stimulus of Sensations to form White.

Any observations made to secure quantitative results with a fatigued retina will be best discussed with the aid of a percentage table of equal stimulation of the three sensations to form white. This will be found in Table LXVIII., for a spectrum of the arc light with horizontal carbons with which all the observations in this chapter were made as a source.[1]

Fatigue by White and the Law of Fatigue.

In regard to the above table, and the fatigue which will be referred to it, attention must be directed to the fact that if the fatigue of the retina is by a white beam, a similar white observed by such an eye will be merely darker than the latter, and no change in colour will be

[1] In this chapter the ordinates of the sensations for equal stimulus to give white are denoted by R′S., G′S., and B′S., instead of RS., GS., and BS., which are the symbols for the "luminosity" sensation.

observed. If the two whites are compared together by the two eyes, the fatigue white will appear a dark grey. It follows, then, that the three sensations on the "equal

TABLE LXVIII.—*Calculated from Table XL., columns* 4, 7, *and* 8, *page* 244.

SSN.	λ	R′S.	G′S.	B′S.	Ratio of R′S. to G′S. (GS. = 1).
64	7217	100	...	...	100
62	6957	100	...	...	100
60	6728	100	...	...	100
58	6521	97	3	...	32·3
56	6330	90·2	9·8	...	9·21
54	6152	81	19	...	4·21
52	5996	70·7	29·3	...	2·41
50	5850	57·5	42·5	...	1·353
48	5720	47·2	51·2	1·6	·922
46	5596	41·6	56	2·4	·743
44	5481	37·5	59·5	3·1	·631
42	5373	33·9	61·2	4·9	·554
40	5270	29·7	62·1	8·2	·486
38	5172	25·8	60	14·2	·43
36	5085	21·8	56	22·2	·369
34	5002	16·8	47·1	36·1	·351
32	4924	11·6	34·2	54·2	·339
30	4848	7·8	22	70·2	·355
28	4776	5·7	14·1	80·2	·404
26	4707	4·3	7·7	88	·558
24	4639	3·45	3·67	93	·94
22	4578	3	1·66	95·4	1·81
20	4517	2·71	·68	96·6	3·84
18	4459	2·47	·35	97·2	7·06
16	4404	2·32	·15	97·5	15·5
14	4349	2·22	...	97·8	...

stimulus" scale, when fatigued by white, will cause the three ordinates to be equally diminished. Again, if the fatiguing colour be that at SSN. 48·6, where the R′S. and G′S. are equal, then the R′S. and G′S. in any colour in

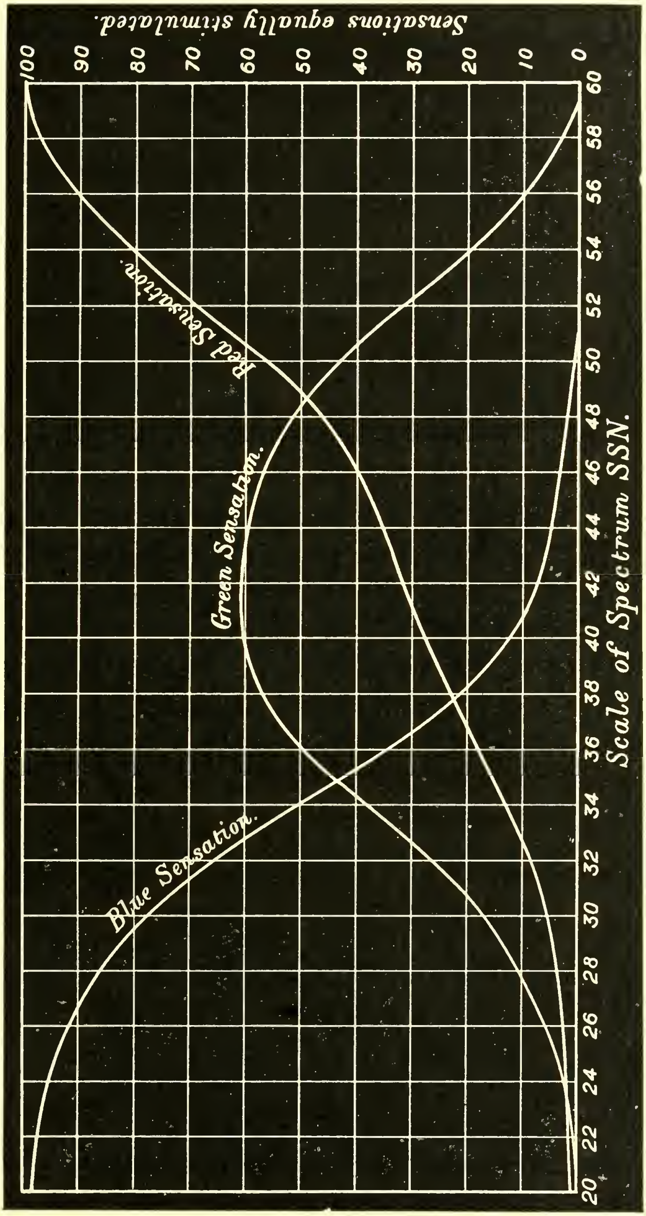

Sensations equally stimulated.
100 90 80 70 60 50 40 30 20 10 0
Red Sensation.
Green Sensation.
Blue Sensation.
Scale of Spectrum SSN.
20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60

Fig. 98.

which there are both sensations will be equally affected. Thus, if the fatigue induced makes the R′S. and G′S., one-half the unfatigued sensations, and a colour, of which the normal composition is, say, 1 R′S. to 2 G′S., is to be observed. This fatigue will only make the colour $\frac{1}{2}$ R′S. to 1 G′S., or the proportion of R′S. to G′S. remains the same. But if the eye fatigued with this colour observes a red in which there is no G′S., the only effective fatigue will be that of the R′S.

Examples of Fatigue.

Between SSN.'s. 40 and 42 there is a ray in which the ordinates of the G′S. is twice as large as that of the R′S. If this be the fatiguing colour, any other colour observed with the fatigued eye (except in the extreme red) will be altered in hue as the fatigued R′S. and G′S. are unequal. As an example, let the fatigue be such as to reduce the original R′S. to $\frac{1}{4}$ R′S.: the fatigue of the G′S. will be twice as great as that of the R′S.

Let the patch of colour be, say, that of SSN. 50, whose composition is R′S. 54·5 to G′S. 42·5. The fatigue will make the R′S. $= \frac{54·5}{4}$ or 13·6, and the G′S. $= \frac{42·5}{2}$ or 21·25. This is a ratio of G′S. to R′S. of 1 to ·64 (see column V. of Table LXVIII.), or the colour the fatigued eye would see would be about SSN. 44—that is, the yellow of SSN. 50 would be seen by the fatigued eye as the green of SSN. 44.

At a SSN. between 38 and 36 (see Table LXVIII.) there is a colour in which the ordinates of the R′S. and the B′S. are equal, but the G′S. has an ordinate which is largely in excess of the other two. Fatigue

given with this colour is practically fatigue with the amount of G′S. which is in excess of the amount necessary with the other two sensations to form white, except where there is no R′S. or B′S. in the colour.

An actual measure of a match made will be of use to illustrate the observations recorded in the next table.

Fatigue was made by a fairly bright red at SSN. 59·8, which is pure red sensation, and the colour to be matched when observed with the eye thus fatigued was SSN. 48·7 where the R′S. and G′S. are equal.

The match made with an eye unfatigued was found to be at SSN. 34·3, but it was very pale. The R′S. had therefore diminished from 1 to ·35 nearly. Previously a measure of the luminosity of SSN. 59·8 had been made with the fatigued eye and the unfatigued, and found to be as 10 to 29 or as ·34 to 1. Now, there is practically no white in the colour of SSN. 48·7, but a large amount at SSN. 34·3. When the fatigue changes the former into a green, the nearest spectrum colour to match seems very pale, hence the green produced by fatiguing the eye is a green much purer than any spectrum green seen with an unfatigued eye.

Matching the Spectrum Colours when Fatigued by Red.

The following is a good illustration of the matches that can be made when the eye is steadily fatigued with a pure red of constant brightness, and the pupil is submitted to its action till a fair balance of fatigue and recovery is struck before an observation is made.

TABLE LXIX.—*Fatigue by the Red Ray at SSN.* 59·8.

Fatigued Eye Observed [1] SSN.	Unfatigued Eye Match [1] SSN.
58·6 [2]	Unchanged
56	53·4
53·34	49·64
50·7	39
48·6	34·5
45·4	32·2
42·8	33·5
40·1	34
37·5	32
32·2	Unchanged
29·6	31·2
27	30·15
21·7	29·6
16·5	20

The first point to call attention to in the above is that from SSN.'s 56 (in which there is only a small quantity of G′S.) to 32·2 (where there is no change in hue capable of being measured accurately), the matches are throughout *lower* in SSN.'s than the fatigue colour. In column VI., Table LXVIII., it will be seen that at that SSN. (32·2) the ratio of red to green is at its minimum. From this number to SSN. 16 the readings of the matches are always *higher*. In both these divisions of the spectrum the smaller luminosity of the red in the fatigue colour is therefore always shown in its match. [This is a direct general confirmation of the truth of the percentage curves of the three sensations, and therefore of the luminosity curves from which they were derived.]

[1] The numbers in this scale are apparently awkward places in the standard scale, to which everything is referred; so far they are the numbers which are derived from a temporary scale. The fatigue colours were whole numbers.

[2] The wave-lengths of SSN.'s of whole numbers will be found in Table XXXVIII. and other tables.

Percentage Composition applied to Colour Blindness.

[Attention must be called to the fact that the "equal area" or "equal stimulation" curves apply not only to normal vision, but also to colour blindness. The difference between the two is that the ordinates of either one or two of the colour blind's luminosity sensation curves have to be multiplied by a higher factor or factors than is applied to the normal vision curves. It is due to this that the following method of finding the factor of fatigue is possible. When the factor of any sensation fatigue is found, the equal area curve for that sensation can at once be calculated.]

Obtaining the Factor of Fatigue.

Studying each observation in detail, so far as is necessary, it will be found that the amount (or factor) of fatigue of the retina is a fixed one when the observations are made as described. To exemplify the method of calculation, one of the observations may be taken in which there is a large proportion of R′S. to G′S., say SSN. 53·34. The match to this colour is at SSN. 49·64.

SSN.'s 53·32 and 49·64 have for their sensation compositions—

	R′S. G′S.
SSN. 53·32	78 + 22
SSN. 49·64	56 + 44

The only alteration made in SSN. 53·32, when the fatigued eye observes it, is a diminution of the R′S.; the G′S. remains unaltered. In the match there is, of course, the normal proportion of R′S. to G′S. If, then, we make the G′S. of the fatigue and the match composition the

same, we can directly compare the R′S. in the fatigue colour with its R′S. when the eye is not fatigued.

In the case in point it happens that the G′S. in the match colour is exactly half of that in the fatigue colour. Its composition is equally well expressed as R′S. 28 + G′S. 22.

The fatigue R′S. is therefore $\frac{28}{78}$ of the normal R′S. in SSN. 53·32, and the factor of fatigue is ·36 RS.

Taking SSN. 50·7, its match is at SSN. 39. The composition of these two are—

$$\text{(SSN. 50·7)} \quad \overset{\text{R′S.}}{61·5} + \overset{\text{G′S.}}{38·5}$$

and

$$\text{(SSN. 39)} \quad \overset{\text{R′S.}}{28} + \overset{\text{G′S.}}{59} + \overset{\text{B′S.}}{9·5}$$

or

$$\overset{\text{R′S.}}{18·3} + \overset{\text{G′S.}}{38·5} + \overset{\text{B′S.}}{6}$$

From this we see that the factor is ·3 of R′S.

In the same way, taking SSN.'s 48·6 and 34·5 having composition of—

$$\overset{\text{R′S.}}{49} + \overset{\text{G′S.}}{49} + \overset{\text{B′S.}}{2} \quad \text{and} \quad \overset{\text{R′S.}}{17·5} + \overset{\text{G′S.}}{60} + \overset{\text{B′S.}}{32}$$

we obtain a factor of ·3 R′S.

At 45·4 we have a match with 32·2, with composition of—

$$\overset{\text{R′S.}}{40} + \overset{\text{G′S.}}{57} + \overset{\text{B′S.}}{2·5} \quad \text{and} \quad \overset{\text{R′S.}}{12} + \overset{\text{G′S.}}{34·5} + \overset{\text{B′S.}}{53}$$

The factor for this, after deducting the white present in the fatigue colour, gives a factor of ·37.

At SSN. 56, when the match is at SSN. 53·4, the compositions are—

R′S.	G′S.		R′S.	G′S.
90·2	+ 9·8	and	77	+ 23

From these we get a factor for R′S. of ·36.

Match Colours from SSN. 37·5.

If we examine the match to SSN. 42·8, which is at SSN. 33·5, we have the following compositions—

R′S.	G′S.	B′S.		R′S.	G′S.	B′S.
35	+ 61	+ 4	and	16	+ 44	+ 40

After deducting the white in fatigue colour from both, we have—

R′S.	G′S.	White.		R′S.	G′S.	B′S.	White.
31	+ 57	+ 4	and	12	+ 40	+ 36	+ 4

Treating these compositions in the same way, we get as a factor ·55 R′S. This increase requires an explanation. The G′S. to R′S. in the match colour is 1 to ·3, and turning to Table XL. it will be seen that there is no colour which has so low a ratio; hence the eye has to do the best it can in finding a match. The same is the case with the next two numbers. In Chapter XVII. it will be seen that from SSN.'s 36 to about 56 the blue which is added by the white light is ignored by the eye, and the hue of a colour is judged by R′S. and G′S. only, but that after SSN. 34 is passed (towards the blue) this no longer holds good. It is the same also in the matching of the "fatigue colours." For instance, let us consider SSN. 32·2, which matches itself. Its composition is—

R′S.	G′S.	B′S.
12	+ 34·5	+ 53

The average factor for the R′S. is ·34.

If we multiply the 12 R′S. by this number, we have R′S. 4·1 in the fatigue colour.

There is therefore no change in it except a greater degree of paleness in—

$$\overset{\text{R}'\text{S.}}{12} + \overset{\text{G}'\text{S.}}{34{\cdot}5} + \overset{\text{B}'\text{S.}}{53}$$

and

$$\overset{\text{R}'\text{S.}}{4{\cdot}1} + \overset{\text{G}'\text{S.}}{34{\cdot}5} + \overset{\text{B}'\text{S.}}{53}$$

Converting these two equations into sensation and white, we get—

$$\overset{\text{G}'\text{S.}}{22{\cdot}5} + \overset{\text{B}'\text{S.}}{41} + \overset{\text{W.}}{36}$$

and

$$\overset{\text{G}'\text{S.}}{30{\cdot}4} + \overset{\text{B}'\text{S.}}{49} + \overset{\text{W.}}{12{\cdot}3}$$

The mixture of white and the green and blue sensations are paler in the first than in the second equation, but the general *hue* would be the same. This is the case in all degrees of red fatigue tried; the match at SSN. 32·2 is invariably that SSN. itself, the only difference being paleness, the BS. differing but little in each equation.

One more match must be considered, viz. that at SSN. 21·7, which when it was a fatigue colour was matched at SSN. 29·6.

The composition of SSN. 21·7 is—

$$\overset{\text{R}'\text{S.}}{2{\cdot}9} + \overset{\text{G}'\text{S.}}{1{\cdot}6} + \overset{\text{B}'\text{S.}}{95{\cdot}5}$$

the *R′S. being in excess of the G′S.*

Taking ·34 as the factor, we get R′S. 1 (nearly), and this is all used up in making the white, and the composition becomes—

$$\overset{\text{W.}}{3} + \overset{\text{G}'\text{S.}}{{\cdot}6} + \overset{\text{B}'\text{S.}}{94{\cdot}5}$$

SSN. 29·6 has a composition of—

$$\begin{array}{ccccc} \text{R}'\text{S.} & \text{G}'\text{S.} & \text{B}'\text{S.} & & \text{White} \quad \text{G}'\text{S.} \quad \text{B}'\text{S.} \\ 6{\cdot}6 + 15 + 78{\cdot}4 & & & \text{or} & 19{\cdot}8 + 8{\cdot}4 + 71{\cdot}8 \end{array}$$

the G′S. being *greater* than the R′S.

Reducing the last composition to make the G′S. the same as that of the fatigue colour, we get—

$$\begin{array}{c} \text{W.} \quad \text{G}'\text{S.} \quad \text{B}'\text{S.} \\ 1{\cdot}4 + {\cdot}6 + 5{\cdot}5 \end{array}$$

The ratio of white to G′S. is not very different in the two, and the eye ignores the excess of B′S. in the first. [It must be recollected that the *luminosity* of the B′S. is 110 times smaller than that shown as B′S.]

In this case the fatigue alters the ratio of R′S. to G′S. to such a degree that the match lies on the other side of the *second point of intersection of the red and green sensation curves*, viz. at SSN. 23·6. (When the factor of fatigue is much smaller, the fatigue colour has to be closer to SSN. 23·6 before the match lies on the other side.)

Treating all these fatigue colours and these matches as we have done in this observation, it will be found that when the white has been deducted from their composition, after the fatigue factor has been applied to the former, the residue *in each* will be either R′S. + B′S. or G′S. + B′S., and never R′S. + B′S. in one and G′S. + B′S. in the other.

Fatigue Matches with smaller Brightness of Red.

A record of observations made with the fatiguing red reduced to closely one-sixth of that used in the last record, Table LXIX., is shown in the next table. The

factor of red fatigue is calculated in the same way as before. Alongside is another record where the fatigue was induced by a patch of "red lithium" light reflected from a card which had a luminosity for the D light of 2 candles at 1 ft. distant from the screen. This makes the red light equal to closely one-fifth of a candle. The factors derived from this record are also given.

TABLE LXX.

Record of Observation with the Eye Fatigued by "Red Lithium Light," about one-sixth that given in Table LXIX.				Record of Observation when the Eye was Fatigued with "Red Lithium Light," of a Luminosity of about one-fifth candle at 1 ft. from Screen.			
Fatigued Eye observed SSN.	Unfatigued Eye Matched with SSN.	Factor of R'S. calculated.	Remarks.	Fatigued Eye observed SSN.	Unfatigued Eye Matched with SSN.	Factor of R'S. calculated.	Remarks.
58·6	No change	...	...	...	...	...	...
56	54·4	·58	...	56	...	...	...
53·3	52	·63	...	53·3	52·8	·81	...
50·7	48·1	·54	...	50·7	50·2	·87	...
48·6	44·3	·61	...	48·6	47·4	·82	...
45·4	40	·59	...	45·4	42·8	·82	...
42·8	39·1	·61	Mean factor ·61.	42·8	39·8	·8	...
40·1	35·9	...	Beyond 42·8 no factor could be calculated, as proportion of G'S. to R'S. was impossible, being smaller than that given in Table LXVIII.	...	...	...	...
37·5	35·9	...		37·5	36·4	·75	Mean factor for R'S. 81
34·9	33·3	...		...	...	...	...
32·2	No change	...		32·2	33·4 And no change	...	Each reading seemed good
29·6	32·7			...	...	...	...
27	29·1	...		27	28·5	...	...
21·7	27·2	...	...	21·7	28	...	...
16·5	28	...	...	11·2	21·7	...	The violet becomes blue

In the record of matches given, the lowest number recorded is SSN. 16·5. Below this the matches could not be made with the highest factor of fatigue (·34) given, as the colour disappeared entirely from view to

the fatigued eye, though still perfectly visible to the eye which was unfatigued. It was curious and interesting to see the colour (which was always much bluer) gradually appearing.

(When the retina is fatigued by a colour, there is always a certain amount of general insensitiveness induced, and what Burch calls dazzle effect, as measurements have shown, in several parts of the spectrum. A reference to pages 186–7 will give the probable reason of this, for although there only an example of the effect of the illumination of the retina by white light is shown, yet the same applies when the retinal illumination is a spectrum colour.)

At SSN. 10, at which point there are only red and blue sensations present, the green being absent, the violet became a dark blue, showing the partial obliteration of the R′S.

Matching the Spectrum Colours when Fatigued by Green.

An example of fatigue with a green[1] ray will now be recorded, the ray being that which has equal amounts of R′S. and B′S. and the large excess being G′S. Such a ray has been discussed on pp. 370–1.

The matches for this green fatigue were made by another observer independently. A large number of fatigue observations have been made by him, as also by the writer. The factors derived from the measures are given in the third column, and, as in Table LXX., the measures of a diminished fatigue caused by looking at a card at M illuminated by this same colour is given.

[1] It may be said that to the author the constancy of the fatigue by the red ray is more readily obtained than by the green.

Table LXXI.

Record of Observation with the Retina Fatigued with a Green Ray at SSN. 41·6.				Record of Observation with the Retina Fatigued with a Green Ray at SSN. 36·6 if the Luminosity of the D Light=one-fifth candle at 1 ft. from the Card Screen.			
Fatigued Eye observed SSN.	Unfatigued Eye Matched with SSN.	Factor of G'S. calculated.	Remarks.	Fatigued Eye observed SSN.	Unfatigued Eye Matched with SSN.	Factor of G'S. calculated.	Remarks.
58·6	58·6	...	No measurable change.	58·6	58·6	...	...
56	56	...	No match, fatigue pink.	56	56	...	No measurable change.
53·3	54·6	·63	Fatigue still rather pink.	53·3	54·5	·63	...
50·7	52·4	·63	Fatigue a little blue.	50·7	51·35	·87	...
48·6	50·9	·58	Good match.	48·6	49·75	·78	...
45·4	48·8	·60	...	45·4	47	·81	...
42·8	46·6	·46	...	42·8	51·15	·80	...
40·1	44·7	·67	...	...	...	...	...
37·5	41	·65	* The amount of R'S. is the smallest and all of it is taken to form white. Only green and blue remain with the white. † Unfatigued colour very much paler. ‡ Practically no change.	37·5	38·6	·82	...
34·7*	36	...		...	...	...	...
32·2	29·4	...		32·2	33·5	...	See Remarks.*
27†	25	...		27	23·1	...	Paler.
21·7†	22‡	...		21·7	21·7	...	No change.
16·5†	16·5	...		11·2	11·2	...	No change, but darker (the G'S. was nil, and there was only fatigue of the R'S. and B'S.).

By this method of matching we have established the fact that we can find the factor of fatigue for the red and green sensations. If the factor of fatigue is the same as the factor of the sensations as described in preceding chapters, of the incompletely colour blind, then the luminosity curves measured with a fatigued eye ought to obey the same rule as those measured by the colour blind.

Luminosity Curves (of Equal Areas) of the Colour Blind pass through one point in the Normal Luminosity Curve.

Dr. Watson has shown that theoretically the luminosity curves of all degrees of colour blindness, and with approximately the same degree of "yellow spot" pigmentation when reduced to equal areas, ought to cut the normal curve at a point where the ordinate is that of SSN. 48·6, the place in the spectrum where the R′S. and G′S. of the "equal sensation area" curves cut.

TABLE LXXII.—*Luminosity Curves all reduced to Equal Areas (see page for Luminosities).*

SSN.	Normal.	Completely Green Blind.			Completely Red Blind.				
		E.	F.	D.	G.	H.	K.	L.	X.
62	2	2·8	2·8	2·8	...	...	...	...	...
60	7	9·9	10·7	10·1	...	...	...	...	...
58	21	28·2	30·8	31·2	...	...	...	...	·7
56	50	64·8	67·8	64·8	11·3	10·3	9·4	10·1	7·4
54	80	105·7	100·5	101·4	27·7	25·7	23·8	23·5	24·7
52	96	112·7	115·7	113·3	56·7	56·5	45·9	57·1	49·8
50	100	105·7	108·8	104·7	92·2	82·3	87·8	83·9	82·6
48	97	94·5	91·6	93	107·2	102·8	107·2	100·8	105·7
46	87	78·9	79	78	112	111·3	110·6	110·8	108
44	75	63·4	65	64	104	109·7	104·6	107·4	104
42	62·5	50	49·4	49·8	88·8	95·9	94·7	94	90·7
40	50	38·2	37·3	37·3	73·1	83·9	78	77·3	79·2
38	36	23·3	25·4	25·3	51·9	58·2	60·6	57·1	61·1
36	24	14·1	15·5	16·7	32·4	39·4	41·8	33·6	42·9
34	14·2	8·7	8·8	10·1	20·5	22·3	22·8	22·8	23·1
32	8·5	6·3	4·8	7	13	13·7	14·7	14·8	14·9
30	5·7	4·8	3·5	5·1	8·2	9·6	8·4	10·7	9·9
28	4	4·2	2·8	3·9	7·5	6·9	6·7	8·7	6·6
26	2·8	3·5	2·3	2·9	6·5	3·4	4	6·4	4
24	1·9	2·8	1·8	2·1	4·8	2·4	2·7	3·4	3·1
22	1·4	2·4	1·4	1·7	3·8	1·7	1·7	2·4	2·5
20	1·1	2·1	1·1	1·4	2·7	1	1	1	1·8

Table LXXII. shows the curves given in Chapter XIX. of the observers who had complete red or green blindness made of equal areas. Table LXXIII. shows the curves of some of the incompletely colour blind persons mentioned in Chapter XX. and the following chapters, also made of equal areas, and also those of completely colour blind (·5 R′S. and ·6 G′S.) calculated from Table XXXVIII. All these curves cut in the place named above.

TABLE LXXIII.—*Partially Colour Blind from Chapters XX., XXI., &c. reduced to Equal Areas.*

SSN.	Normal Luminosity.	W. × 1·15	N. × 1·37.	N.W. × 1·12.	Z. × 1·32.	Incomplete Blindness.			
						⅓ G′S.	⅓ R′S.	0 G′S.	0 R′S.
62	2	...	...	...	...	2·5	1·23	2·8	...
60	7	2·9	9·8	3·3	4·6	8·7	4	10	...
58	21	9·1	28·6	11·2	15·8	26·4	13·4	29·3	·7
56	50	23	65·8	33·6	35·6	60·8	33·7	68	7·5
54	80	48·9	99	58·2	62	93·6	59·5	104	25·5
52	96	72·4	112·3	78·4	81·8	107·3	79	117·8	51·5
50	100	94·9	105·6	90·7	96·4	104·5	93·5	107·2	83·9
48	97	106·4	92·7	97·4	101·6	94·9	100	94	106·5
46	87	106·4	78·2	100·8	97·7	81·2	94·5	78	109·6
44	75	97·7	63·6	96·6	88·4	67·6	85·7	63·2	103·1
42	62·5	84	50·5	80·6	75·2	54·9	73·5	49·5	93
40	50	71·3	39·2	70	62	42·4	61·7	37·2	80·7
38	36	54·6	26·6	57·5	45·7	29·6	45·4	25·4	61
36	24	36·8	16·8	25·7	34·8	19·4	30	15·8	42·7
34	14·2	23	10·5	14	20	11·1	18·7	8·9	21·7
32	8·5	13·8	5·4	11·2	10·6	6·9	11·4	5·4	16
30	5·7	9·2	4	5·6	5·7	4·35	7·5	4·4	10·2

Fig. 99 shows the luminosity curves of the normal eye, completely green and red blind, and of persons having only $\frac{1}{3}$ R′S. and $\frac{1}{3}$ G′S., and shows how completely accurate the intersections are.

If fatigue induces temporary colour blindness, then

the luminosity curves taken with the fatigued eye should also cut the normal curve at the ordinate of SSN. 48·6.

Method of obtaining a Luminosity Curve with a Fatigued Eye.

To obtain the fatigue luminosity curves, a rather different arrangement had to be made from that of

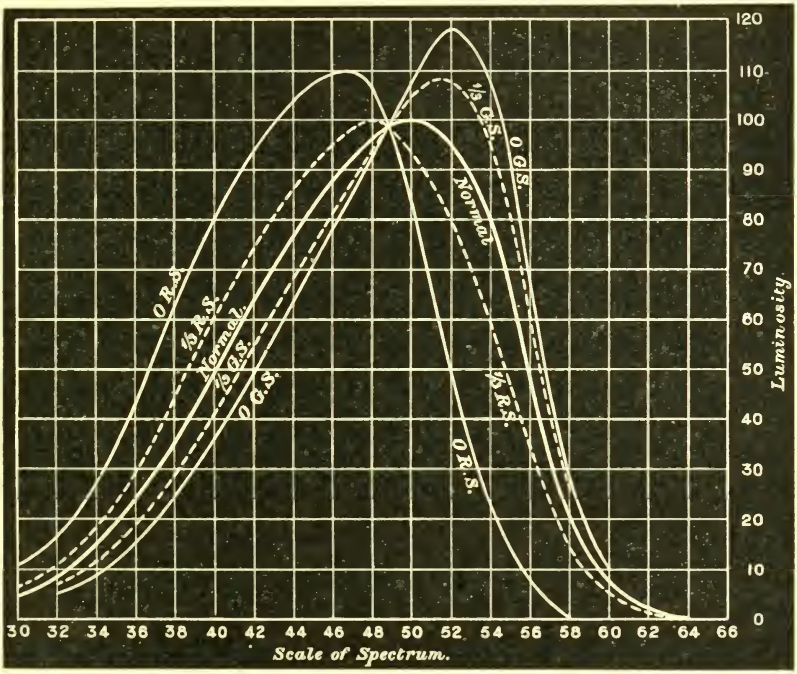


FIG. 99.

Fig. 97. Much of the description of that figure applies to Fig. 100. Only one screen is required.

The spectrum through A remains unaltered, but no third spectrum is required. The white light is used as

in ordinary luminosity measures, falling on C is used as a comparison light, a rod, R, being placed in the path of the beam from A and the white light to form a patch of colour and white side by side. In the white beam an annulus is placed to reduce the luminosity of the white (see p. 40). The fatigue is caused by the ray from the

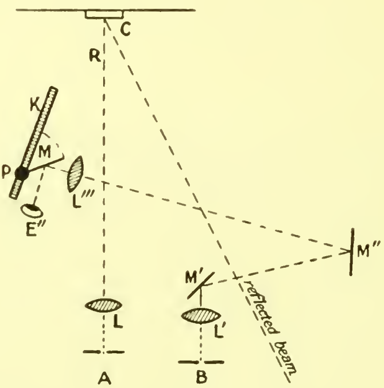


Fig. 100.

second spectrum B, which has two mirrors M′ and M″ placed in its path to reflect it to M and thence to E″.

Luminosity Curves obtained with a Fatigued Retina.

The measures in Table LXXIV. are those of the luminosity of a spectrum of which the source of light was the crater of the positive pole of the electric light, the positive pole being horizontal. (Table XL., p. 244, should be consulted.) The fatigue was induced by "red lithium" light.

Table LXXIV.—*Luminosity of the Spectrum measured*—(1) *by an Unfatigued Eye*; (2) *by an Eye Fatigued with Red Light at the place of the Red Lithium.*

SSN.	Luminosity of Unfatigued Eye.	Luminosity of Fatigued Eye.	Unfatigued Colour.	White.	Fatigue Colour.	Fatigue White.
59·8	10	8	Red	White	Red	Pale green
58·6	17·3	14	Red	,,	,,	,,
57·3	32·2	25	Very red scarlet	,,	Reddish	,,
56	48·3	44	Red scarlet	,,	,,	,,
54·6	66	58·5	Scarlet	,,	Pale yellow	,,
53·3	73	70	Orange	,,	Yellow-orange	,,
52	84·5	80	,,	,,	Pale yellow	,,
50·7	92	90	,,	,,	Bright yellow	,,
48·6	100	100	Greenish yellow	Pinkish	Green	,,
46·7	98	100·5	Yellow-green	,,	,,	,,
45·4	92	96	Green	,,	,,	,,
44·2	87	92	,,	,,	Pale green	,,
42·8	78	81·5	Pure green	,,	Very pale green	Very pale blue
41·4	67	73	,,	,,	,,	,,
40·1	58	60·5	Green	,,	Pale slate colour	Green
38·8	48	52	Full green	,,	,,	,,
37·5	38	43	Blue-green	,,	Very pale bluish green	Very pale green
36·1	28	33	Slight green-blue	,,	Dull grey	Very pale bluish green
34·9	22	24·5	Blue-green	Yellowish	,,	Pale bluish green
33·5	14	16	Greenish blue	,,	Grey	,,
32·2	9·5	11	Blue	Dirty yellow	Blue	Very pale green
29·6	5	8·5	,,	Yellow	Strong blue	,,
27	4·2	5·5	,,	,,	,,	,,
24·4	2·8	5·5	Reddish blue	Amber	Blue	Amber
21·7	2·1	4·8	Nearly purple	,,	,,	Greenish yellow
16·5	1·34	2·7	Purple	,,	,,	Buff

The unfatigued colours and white, and also the fatigued colours and white, are given. When these numbers are graphically shown, the following are the luminosities at whole numbers of the scale.

TABLE LXXV.

SSN.	Unfatigued.	Fatigued.
60	8·7	8
58	21·5	19
56	48·3	44
54	70	64
52	84·7	80
50	96·2	94
48	99·9	101
46	95	99
44	85·3	89
42	72	77
40	56·1	60
38	41	45
36	27·5	30·5
34	15·8	19
32	8·9	10·5
30	6·2	8·5
28	4·6	7·3
26	3·5	6·1
24	2·7	5·2
22	2·2	4·3
20	1·76	3·5
18	1·48	2·8
16	1·29	2·2

In Table LXXIV. the measurements of luminosity at 48·7 were the same for the unfatigued eye as that for the fatigued eye on the annulus scale, and show 100. When making the observations the luminosity measures were made with the eyes unfatigued. The eye was then fatigued by the red, and when the fatigue and recovery were a balance the mirror M was sharply turned against K. (Fig. 99) and the white altered till the luminosities appeared equal. Three or four measures were made and the mean taken as correct.

We can now apply Method I., Chapter XX., for obtaining the amount of fatigue of the red sensation.

Taking two numbers widely apart, viz. SSN.'s 56 and 36, we form the two necessary equations—

$$\text{SSN. 56 is } 48{\cdot}3 - 44z = 46{\cdot}1y$$

$$\text{SSN. 36 is } 27{\cdot}5 - 30{\cdot}5z = 12{\cdot}7y$$

These equations make $y = {\cdot}303$, $z = {\cdot}776$, $x = {\cdot}697$ as the factor for R′S. (y being the deficit; see p. 299).

Again, from SSN.'s 56 and 46 we get—

$$48{\cdot}3 - 44 = 46{\cdot}1$$

$$95 - 99 = 59$$

$$y = {\cdot}326,\ z = {\cdot}75,\ x = {\cdot}674$$

SSN.'s 54 and 44 give—

$$70 - 64z = 68{\cdot}3y$$

$$85{\cdot}3 - 89 = 49{\cdot}7y$$

$$y = {\cdot}316,\ z = {\cdot}782,\ x = {\cdot}684$$

Taking SSN.'s 50 and 42, we get from the equations—

$$y = {\cdot}329,\ z = {\cdot}766,\ x = 671$$

SSN.'s 58 and 38 give—

$$y = {\cdot}325,\ x = {\cdot}675,\ z = {\cdot}768$$

SSN.'s 50 and 40 give—

$$y = {\cdot}313,\ x = {\cdot}687,\ z = {\cdot}783$$

The mean value of x is ·68 and of z ·77.

The factor of R′S. fatigue has been found by exactly the same method as was done for the "colour blind factor." The luminosity curves of the colour blind eye, and of this fatigued eye cut the normal at SSN. 48·6.

Another example of the luminosity curve taken by an eye rather strongly fatigued by the green at SSN. 37·5 is given.

TABLE LXXVI.—*Fatigued with Green Ray at SSN.* 37·5.

SSN.	Luminosities.		Unfatigued.		Fatigued.	
	Un-fatigued.	Fatigued.	Colour.	White.	Colour.	White.
59·8	10	11·6	Red	White	Red	Pink
58·6	17·3	26·3	,,	,,	,,	,,
56	48·3	64	Scarlet	,,	,,	,,
53·3	73	92	Orange	,,	Scarlet	White
50·7	84·5	103	Yellowish orange	,,	Reddish yellow	,,
48·6	100	100	Greenish yellow	Pinkish white	Very pale yellow	Very pale mauve pink
45·4	92	84	Yellow-green	Pinkish	Yellowish white	Strawberry cream
42·8	78	63	Green	,,	Dusty greenish white	,,
40·1	58	46	,,	Pinkish white	Bluish green	,,
37·5	38	28	Blue-green	Yellowish	Very pale blue-green	,,
34·9	22	15	,, ,,	,,	Pale blue-green	Pinkish
32·2	9·5	8·5	Greenish blue	Dirty yellow	Pale blue	,,
29·6	5·7	6·1	Blue	Yellow	Blue	Pink

From this table the following curve was made :—

TABLE LXXVII.

SSN.	Unfatigued.	Fatigued.
60	8·7	11·5
58	21·5	34
56	48·3	64
54	70	86
52	84·7	100
50	96·2	103
48	99·9	97
46	95	85
44	85·3	75
42	72	60
40	56·1	45
38	41	30
36	27·5	20
34	15·8	11·5
32	8·9	6
30	6·2	5

Treating their luminosity in the same way as in the last table, the following factors were found :—

From SSN.'s 56 and 36—

$$y = \cdot 87,\ x = \cdot 13,\ z = \cdot 735$$

From SSN.'s 52 and 38—

$$y = \cdot 83,\ x = \cdot 17,\ z = \cdot 737$$

From SSN.'s 52 and 40—

$$y = \cdot 86,\ x = \cdot 14,\ z = \cdot 734$$

From SSN.'s 52 and 34—

$$y = \cdot 85,\ x = \cdot 15,\ z = \cdot 732$$

From SSN.'s 56 and 36—

$$y = \cdot 85,\ x = \cdot 15,\ z = \cdot 735$$

From SSN.'s 54 and 44—

$$y = \cdot 85,\ x = \cdot 15,\ z = \cdot 760$$

The mean is closely ·15 for x, the factor of fatigue, and the mean value of z is ·74.

Numerous measures of the luminosity curves of the spectrum with fatigue by different colours and by different intensities have been made, some of which give more regular factors than others, but agreeing to the first place of decimals. To get a steady fatigue and to make a rapid observation of the luminosity are all that is required to give equally good readings as can be made with the unfatigued eye. This part of the fatigue observations is now left, and we shall consider the results of white and violet fatigue.

Colours of the Spectrum when Fatigued by White.

We have already stated that (Fig. 98) white is produced when all three sensations are equally stimulated. The fatigue of the retina by white therefore ought to be instructive. It should confirm the existence of white in a large part of the spectrum as shown in Fig. 84. If some colours of the spectrum are mixed with white, we should expect that, if the white is partially destroyed, the colours should become less yellow (*i.e.* bluer), and this would be indicated by the match with an eye fatigued with white.

TABLE LXXVIII.—*Fatigued with White.*

Fatigued Eye SSN.	Match by Unfatigued Eye SSN.	Remarks.
58·6	58·6	The match colour was slightly paler.
56	56	,, ,, ,,
53·3	53·3	No change which could be made ; match colour a little pinker.
50·7	50·2	Match nearly perfect.
48·6	48·6	No change ; the match colour a shade paler.
45·4	44·9	The match colour was a little paler.
42·8	40·7	,, ,, ,,
40·1	38·1	,, ,, ,,
37·5	33·5	The match was pale.
34·9	31·2	Good match.
32·2	27·6	Match colour paler.
29·6	24·9	The fatigue colour invisible at first ; match paler.
27	27	Fatigue colour invisible at first ; match a little paler than the fatigue colour.
21·7	21·7	No change in hue, but the fatigue colour was invisible at first and the match colour pale blue.
16·5	16·5	No change in hue, but the fatigue colour was a deep purplish blue ; the match colour was a pale purple.

Taking the red end of the spectrum from SSN.'s 58·6 to 53·3, we find that the matching colour was slightly pinker

in hue, but no change in the spectrum colours could be found. The tinge of pink shows that there is a certain very small quantity of white in this part of the spectrum, due either to an immeasurably small quantity of the green and blue sensations being present, or else to the white due to the illumination of the prisms of the apparatus. (A very minute quantity of white added to the spectrum red makes it slightly pink.) The pink is not observed ordinarily, but only in contrast with the fatigued colour. At SSN. 50·7 there is a definite shift of the match colour towards SSN. 48·7, the point at which there is no change in hue by the addition of white (see Chapter XVII.). After SSN. 48·7 the "match" colours always have lower scale numbers than the "fatigue" colours. The matches are therefore all bluer than the fatigue colours—that is, the absence of part of the white makes the fatigue colour less yellow than it is with the normal white present. At SSN. 27 the fatigue gives us an impression as to what the colour of the blue sensation is when it is mixed with a comparatively small quantity of white which the fatigue largely obliterated. It seems to be a reddish blue, a colour which near the place of the blue lithium line in the spectrum is, from the sensation curves, a colour which represents the blue sensation, but being mixed with about 80 per cent. of white is not recognised as the colour of the sensation.

Spectrum Colours Fatigued by Violet.

Table LXXIX. shows the fatigue by violet at SSN. 8, in which only red sensations and blue sensations are to be found. The fatigue of R′S. compared with that of B′S. (see Fig. 98) is very small, R′S. 2·2 to B′S. 97·8, and the former can hardly be expected to show.

On the other hand, the fatigue by the B′S. will be much larger.

TABLE LXXIX.—*Fatigue with Violet at SSN.* 8.

Fatigued Eye SSN.	Match by Unfatigued Eye SSN.	Remarks.
58·6	58·6	The colours to the unfatigued eye look yellower than to the fatigued eye, but no match can be accurately made.
56	56	
53·3	53·3	
50·7	50·7	
48·6	48·6	
45·4	47	Match much paler.
42·8	45·4	" "
40·1	44·2	" "
37·5	42	Match still whiter than last.
34·9	43	" seems nearly white.
32·2	40·7	" pale yellowish white.
29·6	42·8	" very white, with a little yellow.
27	35·9	Match nearly white.
21·7	21·7	With unfatigued eye paler than with the fatigued eye.
16·5	5·1	Fatigue colour invisible at first, but very pale, probably owing to feeble luminosity.

From SSN.'s 58·6 to 48·7 there is no apparent change; the fatigue colour looks a little yellower. This small change in hue it was not possible to match. The G′S. and R′S. mixed with the remnant of blue existing in this region, made the fatigue colour yellower, the reason being the same as that given in considering the "white" fatigue. Taking the remarks as to 48·7, it says the match of the unfatigued colour is paler than the fatigued colour. This is to be expected, as only a part of the B′S. has been left in the fatigued retina.

After leaving this SSN. and passing towards the blue end of the spectrum, we have a different state of the sensations. The blue sensation commences to increase rapidly, and the effect of the fatigue is therefore more marked. This the table shows. The fatigue of the B′S.

diminishes the white present, and therefore the colours are purer than seen in the spectrum. As the addition of white makes a colour yellow, the *abstraction of white, as before, makes it bluer.* This is the case till SSN. 21·7, when there is no measurable change, but the "unfatigued" colour is paler than the "fatigued," as could be predicted from the diagram. At SSN. 16·7 the match is found in the pure violet, though it is imperfect and is paler than the fatigue colour, which may be due to the luminosity falling nearly into that which deprives it of any colour.

Many more places in the spectrum were taken as fatiguing colours, and the results show, as stated, that the fatigue factors by all can be classed as red or green incomplete blindness, with the exception of SSN. 48·6. This gives no factor for those colours where all the sensations are found.

The Addition of the Fatiguing Colour to the Match Colours of the Fatigued Colours.

It has already been stated that no "sympathetic action" has been found between the fatigued and unfatigued eyes. A direct proof that this is the case is to be found in the results of experiments made with the "matching" colours and unfatigued eyes. When the factor of fatigue for red or green has been found, the addition of the necessary amount of the fatiguing colour to the matching colours will give the hue of the "fatigue" colour before it has been observed with the fatigued eye. Thus, if the fatigue factor of the red is, say, ·3, the addition of ·3 of the red sensation existing in the "fatigue" colour to the match colour when the luminosities are the same, will give the *hue*

of the former colour before it was matched with the fatigued eye. The same is the case when the fatigue is caused by the green or violet. The easiest plan of procedure is to add the necessary amount of the fatiguing colour to the match to cause its hue to be the same as that of the "unfatigued" colour, and note the addition made. It will be found that the amount added is that necessitated by the factor of fatigue.

Colours of the Spectrum to the Normal Eye.

Below are tables of the colours at the different scale numbers in the foregoing tables of this chapter as they appear to the normal eye when not contrasted with white or any other colour—(1st) when unfatigued; (2nd) when fatigued.

Table LXXX.—*Unfatigued.*

SSN.		SSN.	
61·2	Red.	40·1	Rather bluer green.
58·6	Red.	37·5	Bluish green.
56	Reddish scarlet.	34·9	Greenish blue (viridian).
54·4	Scarlet.	32·2	Blue (pale).
53·3	Red orange.	27	Darker blue.
52·3	Orange.	21·6	Reddish blue (not much red).
51·2	Yellow orange.	19·2	Purple.
50·2	Yellow.	16·5	Violet purple.
49·1	Greenish yellow.	11·2	Violet.
48·1	Yellowish green.	8·2	Violet.
45·4	Green.		
42·8	Slightly blue-green.		

Table LXXXI. shows the colours when the eye has been fatigued—(1) by red lithium red; and (2) by green at SSN. 37·5. The factors of fatigue for both were closely ·5.

Table LXXXI.

SSN.	Colours Fatigued with Red.	Colours Fatigued with Green.
59·8	Red much darker	Bluer and darker
58·6	„ darker, but pale	Redder than unfatigued colour
56	Still pale and yellower	„ „ „ „
53·3	Pale yellow-green	„ „ „ „
50·7	„ „	Pinkish orange
48·6	Bright yellowish green	Pale blue-pink
45·4	"Solid" green	Dirty white
42·8	„ bluer green	„ „
40·1	„ „ „	White slightly blue
37·5	Blue-green rather paler	„ „ „
34·9	„ „ pale	„ rather bluer
32·2	Greenish blue same colour as before fatigue, but paler	Pale blue
27	Saturated light blue	„ violet
21·7	„ blue	Dark purple (when the colour appears)
16·5	„ darker blue	Very dark purple (when the colour appears)
11·3	„ „ „	Very dark purple (when the colour appears)
6·1	Deep blue	
White	A slightly pale blue-green	A rather pale purple

These tables are given, as they will in some measure aid the reader to understand to some extent why names are given to the colours of the spectrum by colour blind persons with varying degrees of colour blindness, which differ from those given by normal vision. In the next chapter it will be seen how great are the differences. By translating the colours of the above table into the language of the colour blind (the foundation of which is the colour they recognise as white), a better idea will be gained of the reason for the difference in nomenclature.

Rapid Fatigue.

Bidwell found that not only did fatigue take place after a prolonged gaze at a colour, but that under certain

conditions it took place after a momentary glance, and was sufficient to produce a fugitive after image of the complementary colour. The condition which governs this is, that the retina shall be darkened immediately before the bright object is viewed. He says: "The retinal nerves, when in darkness, rapidly acquire a state of sensitiveness far exceeding the normal average in the light, but quickly diminishing again under the influence of illumination. The peculiar sensitiveness may indeed be both gained and lost in a small portion of a second, and is therefore very favourable for the rapid generation of negative after images."

Bidwell described methods by which this phenomenon can be shown in a very simple way. By using a balanced disc rotating on a centre, and covering one-half with black velvet and the other with white paper, and at one junction cutting out a sector some 30° in aperture, he was able to show it with great certainty. A red wafer placed on a piece of grey paper is illuminated, and the disc is so placed that the black covers it from view; when the aperture rapidly passes in front of the eye, so that the wafer is seen for an instant through the opening, and the white of the disc shuts it off, immediately there will be perceived a bright but quickly-vanishing greenish-blue image. Bidwell states, and the writer has confirmed it, that if the illumination be strong and the disc rotated with proper speed, no trace of red will be seen at all, and that the only colour seen will be the blue-green after image. A glance at Bidwell's diagram, Fig. 8, p. 25, may throw light on the subject of this rapid succession of negative after images, remembering that instead of white we are using coloured light, and that the short dark interval will now only be dark in respect to the

colour used, and not to the other colours. At a soiree of the Royal Society, Bidwell showed a striking example of this method of viewing after images. He had a picture of a lady in which the hair was indigo blue, an emerald green face, and a scarlet gown, who was represented admiring a sunflower with purple leaves. Seen through the disc revolving some six to eight times a second, the hair appeared flaxen, the face a delicate pink, and the dress peacock blue; the sunflower became yellow, and its foliage green.

In Chapter VIII. is described an apparatus for measuring "flicker" luminosity. By a slight alteration of the apparatus a colour can be thrown on the small square and then be followed by an interval of white light, and this by an interval of darkness, and then an interval of the colour again, and so on. This gives striking after images of the colours, when the revolutions of the flicker wheel is from 60 to 120 revolutions a minute.

CHAPTER XXVI

TESTING FOR COLOUR BLINDNESS

The preceding chapters will have given an idea of the mode which has to be adopted in the laboratory for the testing a person as to his colour vision when the eye is practically dark adapted, and a further reference will be made to certain of the tests therein indicated. The question that now requires consideration is as to tests which are available for the same purpose in daylight where no laboratory is available. The acuteness of sensation for colour is not the same when the eye is saturated with external white light as it is when it has been in darkness for some time. The reason of this is perfectly easy to understand. The three sensations are being perpetually equally fatigued with white light, and they consequently become less sensitive to any colour which falls upon the retina. In making tests we have to avoid being led astray by a person's ignorance of colour nomenclature, though the writer has never met with a case in which colour ignorance was at all pronounced.

The Wool Test.

Holmgren, the Swedish scientist who has given in the past much attention to the subject, recommended that coloured skeins of wool should be employed to diagnose colour blindness. This is based on the ground that a variety of hues and shades of colours in that form could be obtained in commerce. The wools never

appear "shiney," but reflect the light fairly equally in every direction, and they are easily handled. He also made it a *sine quâ non* that the examinee should not be called upon to name colours, but should be merely tested by his picking out those skeins which fairly matched, in colour only, certain standard colours that he selected as efficient. The three colours which he selected were—

A pale green, *i.e.* a green much diluted with white,
A full pink, and
A bright red.

The "confusion" skeins he selected contained different shades of pinks, mauves, violets, neutral tints, browns, dark greens, greens, buffs, yellows, green-yellows, blues, green-blues, and others.

The standard colours selected are most suited for the detection of complete or nearly complete colour blindness rather than for colour blindness which is incomplete and is small.

Take the case of a completely red blind person, when he is told to match the pale green scale, he would (in the language of normal vision) see no red in the white with which the green was mixed, and would select, *besides the correct matches*, a pale yellow or a neutral tint or a buff as a match in colour, for he would distinguish none of the red in the colours which is recognised by the normal eye in them.

A person completely green blind would see no green in the green skein, and all he would see would be his own form of white, a purple. He also would select pale yellows or buffs or neutral tints, and, in fact, would make a match with almost any pale coloured skein, amongst others those which contain a suspicion of red

to the normal eye, the reason being that his white is, in the language of normal vision, a purple, and most of the pale colours would appear pale purple to him, and therefore he would take them as matches to the green skein.

With an incomplete blindness to green, but which was of a pronounced character, the selection would not be so varied. We have seen at p. 265 that a certain amount of colour may be added to white without being perceived. As the green in the pale green scale is slight, the colour may to such an eye disappear in his white and not be diluted. His white would be a very pale purple, and only those coloured skeins which looked of the same whiteness (to him) would be selected.

Taking up the skeins examined by the complete red or green blind and comparing them, it might be very difficult, from the selections made, to determine whether the person was red or green blind.

The use of the next test skein, the pink, would at once determine into which category to place him.

To the completely red blind the red in what is pink to the normal eye is non-existent. He sees the pink as a pale blue, with perhaps a little green in it, which comes from the white, and he will match the skein with any colours which contain blue, whether they contain red or not, thus he will pick out the various shades of pink as matches; they, of course, are as blue to him as the test skein, and he will pick out the mauves and violets, as also the blue skeins.

The completely green blind will see the pink nearly as the normal eye sees it, and will pick out the pink skeins, but will not think of matching the blue or violet or mauve skeins with it, but he will select pale bluish greens, as he sees no green, but only the

pink in them. He may also pick out a white or neutral coloured skein, together with dark brown and dark greens, for the absence of green sensation may make them the colour (though darker than it) of the pink skein. The third skein is a dark scarlet, and the completely red blind would not see the red in the scarlet, but only the dark green. This enables him to match the dark green, and might also place a light green with the test skein. On the other hand, the completely green blind (or nearly completely) would fail to recognise the green in the scarlet, and would select all the scarlet and red skeins, also the brown skeins.

This last test is the weakest of the three test skeins, and would very often fail to detect colour blindness if used alone. If, instead of the dark scarlet a dark brown skein be substituted, much greater facility is given to the detection of even fairly slight colour blindness. The green component then is stronger, and the red blind will match not only dark green but also light green with it. The green blind would be inclined to pick out the browns and the reds.

Except for the fairly pronounced examples of incomplete colour blindness, it is not uncommon for the incomplete colour blind to pass these three tests with but slight errors. In order to detect these cases more surely, the addition of two other test colours besides the brown suffices, and though they may only approximately tell the amount of colour blindness that exists, yet they will indicate that there is colour blindness, and also its nature. The first of these extra tests is a bluish purple. In this colour there is but a small quantity of red, so that the incompletely red blind would fail to notice it, and would make matches

of pure blue with it, and probably add blues with a small quantity of green in them. Such matches would indicate a deficiency in the red sensation. The incompletely green blind would match the proper skeins with it, and very likely make no mistakes.

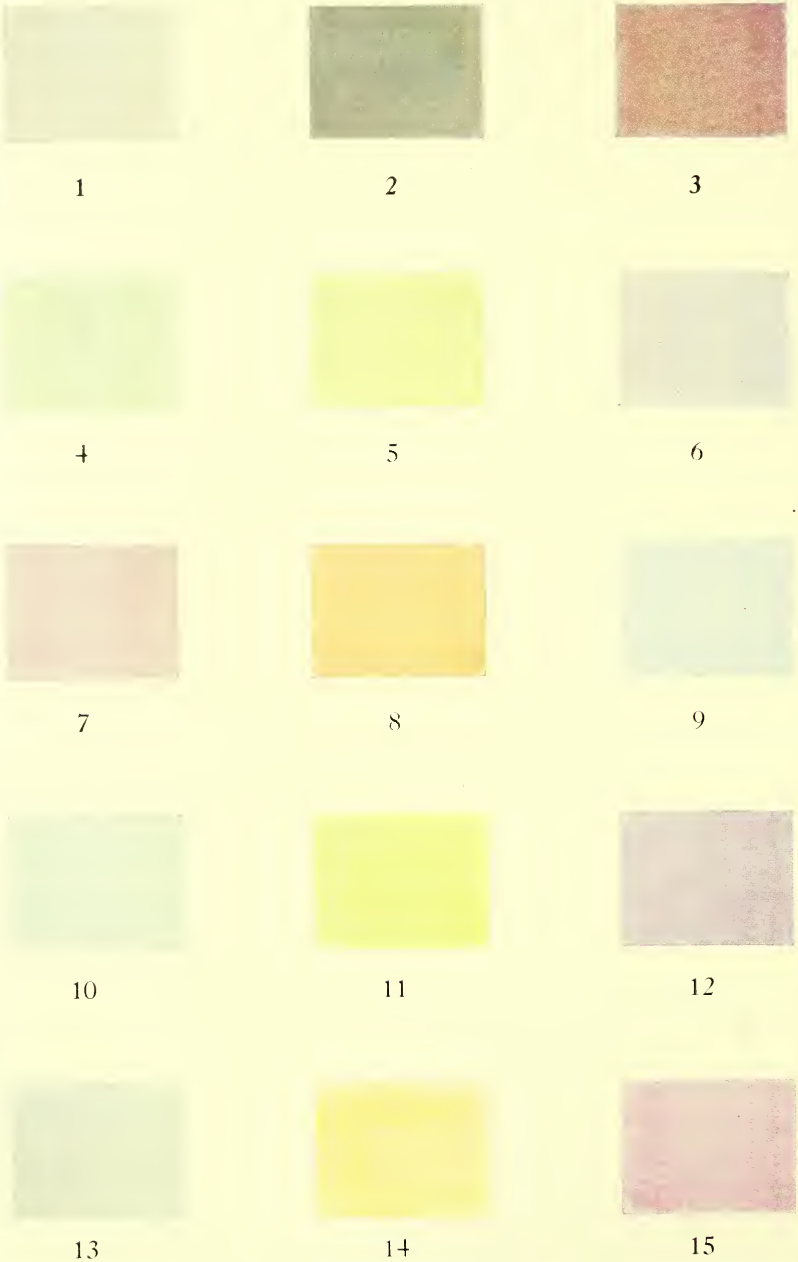
The next test skein should be a slightly pale yellow. A red blind, besides the correct matches, will select skeins in which the green-yellow preponderates, and this may be taken as a sure sign that there is a red deficiency in his sensations. The green blind will, besides the proper matches, pick out yellows which are decidedly on the red side of the test skein hue. Such matches show that there is a green sensation deficiency in the eye. If the test is properly applied, the chances that any notable deficiency in any of the sensations will escape detection are very small. After an examination has been made, if the examinee is asked to name some of the confusion colours, the giving of a wrong name to any of them will confirm what has probably been found out by the matches.

Test by Water-colour Washes.

Another daylight test which the writer has carried out in the absence of the wools is by means of his water-colour paint-box. This is simply a test for those who are not colour ignorant. Before us is a test that was made abroad of the eyes of a certain foreigner, who had no idea that he was or could be colour blind. A piece of drawing-paper, a tumbler of water, the paint-box, and daylight was all that was required.

Pale stripes of rose madder of neutral tint, of viridian (bluish green), aureolin, permanent violet, with vermilion and emerald green, were brushed on

PLATE III.



Series of Water-colour Patches, containing among them
Confusion Colours.

to the drawing-paper, and, when dry, one by one the stripes were submitted and the hue of the wash asked for. The rose madder was named pink, the neutral tint pinkish, the permanent violet correctly, viridian was grey, and so was the emerald green, the yellow aureolin was reddish. These answers were quite enough to convict the examinee of being partially green blind.

Subsequently the same colours were submitted to another person, whose eyes were supposed to be normal.

The faint vermilion was called green, the rose madder was "bluish," the neutral tint was whitish, the viridian was bluish, aureolin yellow was green, and the permanent violet was blue. The examinee was evidently partially red blind. By mastering the principles which underlie the trichromatic theory, it is easy to make tests by coloured materials other than the wools.

In Plate III. the water-colour washes were as follow :—

No.
1. Neutral tint.
2. Neutral tint and a little viridian.
3. ,, ,, ,, ,, vermilion.
4. ,, ,, ,, ,, cobalt blue.
5. Pale neutral tint and a little viridian.
6. ,, ,, ,, ,, ,, rose madder.
7. ,, ,, ,, ,, ,, rose madder and cobalt blue.
8. Pale madder yellow.
9. Pale cobalt blue.
10. Mixture of cobalt blue and viridian.
11. ,, ,, aureolin and cyanine blue.
12. ,, ,, vermilion and blue.
13. Neutral tint.
14. Aureolin.
15. Rose madder.

These, of course, can be supplemented *ad lib.* by washes such as pale vermilion and Hooker's green, &c.

Test by Colour Discs.

A test which can be applied qualitatively as well as quantitatively is that of the rotating colour discs of red and green, with black and white sectors behind the smaller pair (see p. 337). The examinee may make a match in daylight looking through a chromate cell, containing chromate of potash in solution. The angle of the red or green is altered until the two give a yellow which matches in hue the outside disc. The angles of the sectors are noted.

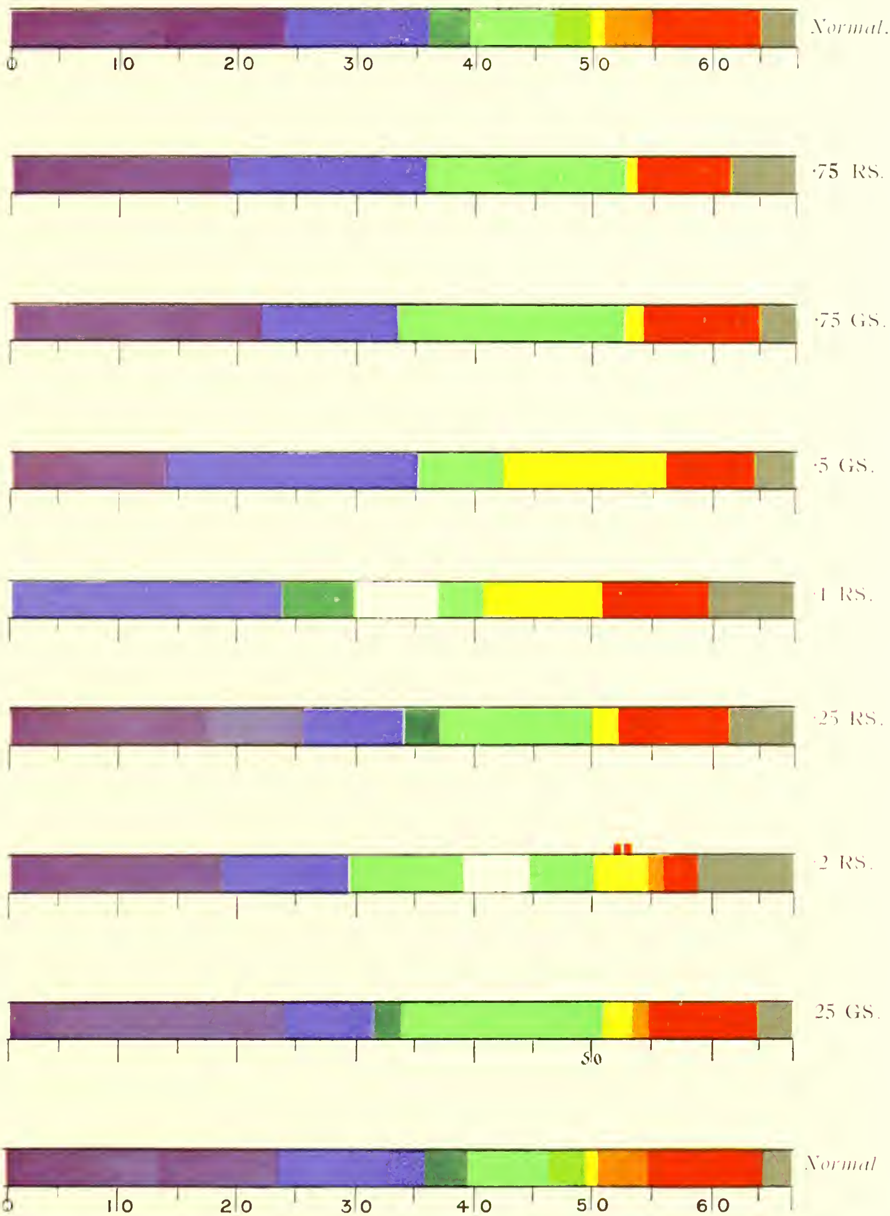
When a colour blind is called upon to make a match, a very small angle should be shown of one of the discs. This will probably be demanded to be increased, the inner disc being said to be either too red or too green. When a match is made, the angles of the discs should be noted and a rough estimate can be made by a comparison of the normal equation with that of the examinee.[1] If the red sector is the greater, the latter will be incompletely red blind; and if the green sector is the greater (compared with the normal), there is incomplete green blindness. A small motor, of course, is most useful for rotating the discs, but there are several mechanical whirling apparatus which can be employed.

Laboratory Tests.

In the laboratory with the colour patch apparatus a very fair idea of the amount of deficiency in the red and green sensations is given by noting the names given to the colours at various parts of the spectrum. In Chapter XVIII. specimens of the colours named by completely and nearly completely red and green blind have been illustrated, as also the alteration in nomen-

[1] This is more fully described in Chapter XXIII.

PLATE IV.



Spectrum Colours as named by persons with different degrees of Colour Blindness.

clature of the colours under differing conditions in the case of a person who was very nearly completely but not quite red blind. In Plate IV. we have illustrations of the spectrum colours named by eight different persons, with varying degrees of red or green blindness, when the colours were shown in patches. One slit in the spectrum was employed, and was placed at the extreme limit of the red end of the spectrum (to the normal eye). The examinee was asked to name the colour, and in the cases of red blindness he usually saw nothing at the extreme red but a faint colourless or green light, due to the small quantity of white illuminating the prism. The slit was gradually moved along the spectrum.[1] The examinee was required to stop the movement when he saw any change in the red, and was asked to name it. The slit was again moved in the spectrum till another change in colour was seen, and this scale number was noted. In this way the whole of the spectrum was submitted for colour naming.

When the extreme violet was reached, the colours were submitted with the motion of the slit reversed. (Of course, as in the two previous plates, no attempt has been made to indicate the luminosity, but only the colour.) There are very marked differences in the colours named by eyes possessing various degrees of colour blindness.[2] The amount of green or red blindness was determined by the methods given in Chapter XX. Again, if a patch of colour be shown alongside a patch of white, those who are completely blind or nearly completely blind to the sensation will match them together when the colour is a green. The com-

[1] In the case of the red blind it was noted when the patch appeared red.

[2] In one case (·2 RS.) above the patch of yellow are two red marks. These marks indicate that on two separate occasions red was named at this position instead of yellow.

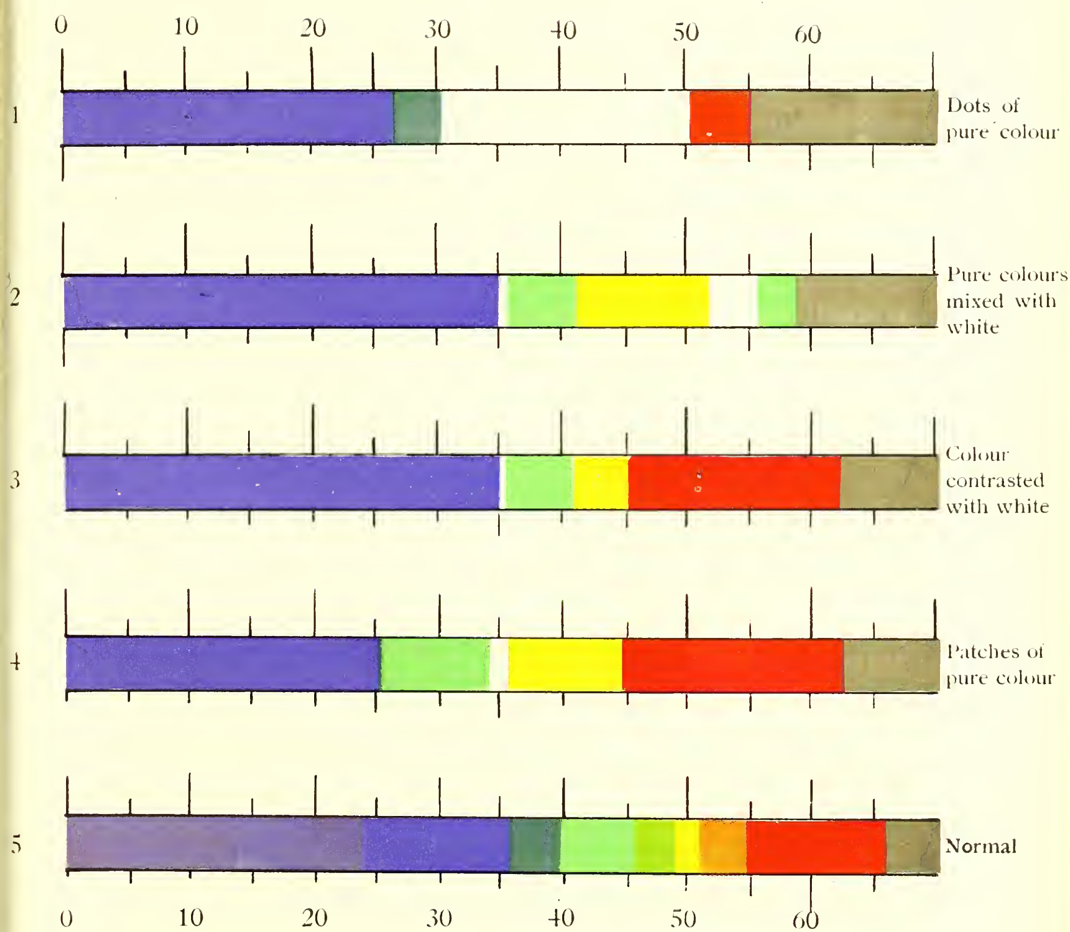
pletely red blind will with the arc light make a match about SSN.'s 34 to 35, and the completely green blind about SSN.'s 36 to 38; the exact position will vary a little, according to the amount of pigment present in the macula lutea. This position is often called the neutral point in the spectrum, and will be found when examining completely colour blind and nearly completely colour blind. In the cases of green blind who have a small factor for green sensation, it may happen that a large band of spectrum may be matched with the white sometimes extending from the red to the blue (see Plate II.). This is easily accounted for, owing to a small amount of colour in a large amount of white escaping detection (see Chapter XIX.). The case cited on p. 300 is an example of this kind.

Dot Test.

Another test (called the dot test) is to throw the different colours on a small white disc about $\frac{1}{8}$ in. diameter, mounted on black velvet, and make the examinee stand at from 12 ft. to 20 ft. away, and name the colours shown. Chapter XII. shows that by diminishing the angular measurement of a patch of colour, it becomes colourless.[1] As one of the colour sensations to the colour blind is less than to normal vision, it follows that the small patch may fail to show a colour to the colour blind when it is quite visible to the normal eye. If the examinee have a red sensation deficiency, the colours in the red end of the spectrum may not be visible at all, or else be nearly colourless. When the factor of

[1] It is shown that the intensity of a patch of light to first lose its colour may be increased tenfold when the size of the patch is reduced to $\frac{1}{8}$ in. diameter.

PLATE V.



Spectrum Colours as named by a person who possessed ·35 of Red Sensation.

the sensation is large, only the dark reds will fail to be seen, though they are quite apparent to the normal vision.

Plate V. shows the striking differences in colour nomenclature given by the same person when the colour patches are shown under differing conditions, such as those above mentioned.

Band No. 5 is the spectrum to the normal eye.

The remaining bands of colours apply to a colour blind whose factor of red sensation was ·35.

Band No. 4 were the colours named when patches of colour only were thrown on the screen, and is comparable with Plate IV.

Band No. 3 shows the colours named when contrasted with a white patch.[1]

No. 2 band shows the spectrum colours as named by the colour blind person when mixed with a small quantity of white light.

No. 1 band shows the names he gives to the spectrum colours when reduced to dots of $\frac{1}{8}$ in. diameter, and observed 16 feet away from the screen.

Plate V. may be compared with Plate II. as examples of the non-recognition of colour by the colour blind, when the spectrum colours are reduced on the screen to very small areas. It will be noticed in both that the names of the colours are very often quite different to those which are given when the patches are larger. The variation is very well shown in Plate V. Here we have colour blindness; and by keeping the intensity constant and diminishing the diameter of the patch, the colour is extinguished sooner than it is to normal vision. The amount of reduction necessary to extinguish depends on the factor of the red or green sensation.

[1] When a normal eye is fatigued with red so that the factor of red fatigue was about the same as the above factor, the white band shown as such in Nos. 2, 3, and 4 appeared green, and the white of the reflected white light was also green.

Lantern Test.

The examination of seamen for colour blindness has been largely carried out for the past twenty years by the writer, and the dot test has formed a valuable aid in ascertaining whether the colour vision was sufficiently good to enable the ordinary red and green lights of ships at sea to be recognised at a distance. Recently a Committee representing the physical and physiological sciences and nautical experts have recommended that the same kind of test should be carried out, but with an oil lantern in a darkened room, in which the eyes of the examinees become "dark adapted."

With this lantern ships' lights as seen at a distance of 500 and 2000 yards can be imitated by illuminating two circular apertures of the necessary diameter with an ordinary oil light, such as is used on board ship, and testing the examinee with different variations of red, green, and white[1] coming through the two apertures. The glasses which give the coloured lights are the same as those in actual use on board ship. The three lights are made of about equal luminosity to the normal eye. It has been found that with factors of red and green blindness as high as ·6 to ·7 there are mistakes made in naming the colours shown both in the spectrum dots and in the lantern, the most common being in the mistaking of white for red, and of green for white, and of the white for green. In cases where the degree of colour blindness is smaller, the red and the green in the lantern are mistaken for one another. It must be recollected that the glasses transmit impure colour, the green light being largely contaminated with white, and the red glass allows yellow rays to pass. This test

[1] Naked oil light.

is less severe, perhaps, than the test with the dots of spectrum colours in one respect; but it has the great advantage of being a practical test, and easily understood by the ordinary person who has no views on theories of colour vision.

The official report[1] which the above Committee issued shows that tests of ordinary ships' lanterns were carried out at Shoeburyness (and elsewhere), the lamps being observed by the colour blind (who had been previously tested in the laboratory) at different distances up to 3000 yards, and gave the same results as with the lantern in the laboratory as to the factors of colour blindness which could just not distinguish the colour of the lights.

Optical Imperfection of the Eye causes inability to recognise Coloured Light.

The writer, a few years ago, when considering other causes than deficient colour sensation which might prevent the recognition of colour, came to the conclusion that the optical condition of the eye might be of such a nature that small discs of coloured light might be taken as colourless or not seen at all. To confirm or disprove his diagnosis, he made his eyes myopic, &c., and observed ships' lights from the seacoast, and also known stars, and found that with about half normal vision ships' lights at 2 miles were sometimes invisible or colourless, and that only stars above the 4th or 5th magnitude could make an impression on the retina. The reasons for such failure which he gave to the above Committee were on the following lines.

[1] *Report to the Departmental Committee on Sight Tests* (Board of Trade), presented to both Houses of Parliament; published by H.M. Stationery Office, 1912.

A point of light such as that coming from a distant star forms an image on the retina which is a disc of a certain size, depending on the diameter of the lens of the eye and its focal length. A light at a certain distance, though not a point, will form a disc image of the same diameter, and beyond that distance the diameter of the disc will not vary, though it will increase within that limit. The coloured light will, whilst diminishing in angular dimensions as it recedes beyond this limit, still show on the retina practically the same size of disc, and the smaller light will be less "dense" on that disc. (Even for normal eyes there is a distance where the eye with normal vision would fail to see the colour; see Chapter XII.)

If the vision be less than normal, the disc formed on the retina by a point of light will be larger than with the normal eye, the diameter depending on the amount of defect in the form vision. Thus the coloured light is spread over a larger area than is the case with normal form vision, and, consequently, say a green light, which will appear to the latter as a disc of green of decided colour, may be seen by the former as a whitish patch, or, in the case of a red, may not be seen at all.

In the Committee's report the result of the practical testing of eyes having less than normal *form* vision for the recognition of ships' lights is given. The distance at which there is a failure to recognise colour is about 2000 to 3000 yards when the vision is half normal.

The laboratory lantern tests give the same results.

[It is, perhaps, to be regretted that in the practical tests carried out during the two fortnights (in the late autumn and spring), no great variations in the clearness

of the atmosphere were met with, as the conditions were all in favour of the colour blind and defective form vision examinees.]

Test by Simultaneous Contrast.

Another instructive test is founded on the answers given as to the colours found by the simultaneous contrast between white and the different colours of the spectrum. The contrasts which the colour blind see appear often to be extraordinary, but when considered in the light of the three-sensation theory they lose what may be called their extravagance. The smaller the factor of the deficient sensation, the more divergent from the normal do the contrast colours of the white become. It is no uncommon answer, for instance, when to the normal eye a colour is green and the white is a salmon colour that both stripes should be called green. The mistakes made very readily indicate the nature and extent of the colour blindness that is being examined. This, of course, is only a qualitative test. As an example of the mistakes that may be made, the following contrasts were observed by an eye which had only ·5 of the normal green sensation :—

Colour shown.	Normal Contrast of White.	Colour to Colour Blind.	Contrast of White to Colour Blind.
Dark red	Green-grey	Green	Red
Brighter red	Green-grey	Red	Pale green
Orange	Blue	Green	Green
Greenish yellow	Umber colour	Pale green	Blue
Pale green	Lavendar	Green	Red
Pure green	Pink	Blue-green	Red
Bluish green	Salmon	Dark green	Pale red
Greenish blue	Yellow	Blue	Green

Quantitative Tests.

In the laboratory, of course, the quantitative tests which have been indicated in Chapters XX. to XXIII. can be employed. When testing by the difference in luminosities of the normal and colour blind persons, the flicker method of getting the luminosity is the easiest plan to adopt, and gives correct results if both normal and colour blind make observations by it. The method of getting flicker luminosity has been described in Chapter VIII.

If a diagram be made like that given in Fig. 99, p. 383, showing three different degrees of red and green colour blindness, say ·7, ·3 and 0, factors of red sensation, calculation is very much shortened.

Making the luminosity of the normal and colour blind the same at SSN. 48·7, the measures of the luminosity of the colour blind can be applied to the different scale numbers of the spectrum, and the ordinates show between which of two curves the examinee's observation lies. A close approximation to the factor of the sensation which is deficient can at once be made. When the luminosities of several scale numbers are taken, they should all give the same factor.

PAPERS BY THE AUTHOR REFERRED TO IN THIS WORK

(1) "The Production of Monochromatic Light." *Phil. Mag.*, Aug. 1885.

(2) "Colour Photometry." *Phil. Trans. Roy. Soc.*, 1886.

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